Computer Simulation of Marine Traffic Systems

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Declaration

No part of this thesis has been submitted for any award or degree at any other institute.

While registered as a candidate for the degree of Doctor of Philosophy the author has not been a registered candidate for another award of the C.N.A.A. or of a university.

Copies of material published in connection with this research are bound at the end of the thesis.

Advanced studies undertaken

Attendance at a course in Operational Research techniques and their computer applications given for the M.Sc. in International Shipping. A weeks full-time course leading to the Department of Trade Radar Simulator Certificate.

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Abstract

A computer model was constructed that allowed two vessels involved in a possible collision situation to take collision avoidance action following the "International Regulations for Preventing Collisions at Sea". The mariners' actions were modelled by the concepts of the domain and the RDRR (Range to Domain/Range-rate). The domain was used to determine if a vessel was threatening and the RDRR to determine the time at which a vessel should give-way to a threatening target. Each vessel in the simulation had four domains corresponding to the type of encounter in which the vessel was involved. Values for the time at which a vessel manoeuvres and the domain radii were determined from an analysis of high quality cine films of the radar at H.M. Coastguard at St. Margaret's Bay, Dover. Information was also taken from simulator exercises set up on the Polytechnic radar simulator. The two ship encounter was then developed to become the multi-ship encounter and eventually was able to model over 400 vessels over a two day period through a computer representation of the Dover Strait.

A further development included a computer graphical representation of a radar simulator running in real-time, and which allowed a mariner to navigate one of the vessels using computer control.

A validation of the computer model was undertaken by comparing the simulated results with those observed from the cine films. Following the validation several examples of the computer model being used as a decision support system were included.

Glossary

A.F.S.O.N.G.	Anglo-French Safety of Navigation Group.
C.A.M.	Collision Avoidance Manoeuvre.
C.P.A.	Closest Point of Approach.
D.w.t.	Dead weight tonnage.
E.I.T.Z.	English Inshore Traffic Zone.
I.M.O.	International Maritime Organisation.
I.R.T.	French Transport Research Institute.
N.A.G.	Numerical Algorithms Group Scientific Library.
N.M.I.	Department of Trade and Industry, National Maritime Institute
O.P.	Orientation Points.
O.R.P.A.T.	Observed Related Port Approach Traffic Simulation.
Own-ship	The ship being controlled by the simulation or by a hypothetical mariner.
P.C.P.A.	Projected Closest Point of Approach.
P.P.I.	Plan Position Indicator.
R.C.	Relative Contour.
R.D.R.R.	Range to Domain over Range-Rate ratio.
R.M.N.U.	Relative Motion, North-up.
R.M.S.U.	Relative Motion, Ship's head-up.
S.D.	Standard Deviation.
T.C.P.A.	Time to Closest Point of Approach.
T.M.	True Motion.
T.S.S.	Traffic Separation Scheme.
U.L.C.C.	Ultra Large Crude Carrier.
V.L.C.C.	Very Large Crude Carrier.

Chapter 1 Introduction

1.1 The need for Traffic Separation in the Dover Strait

The water-way between the south-east coast of England and the Continent carries a large proportion of the world's marine traffic. Besides the large volume of ferries which regularly transport a vast number of passengers and vehicles between the Channel ports, many of Europe's major trade routes converge at these narrows. Since the growth in international commerce in the fifties, the considerable increase in the volume of shipping (Fig.1.1) has led to a corresponding increase in casualties. To quote Cockcroft (1978):

> "For traffic proceeding in random directions on a plane surface the frequency of collisions, if no avoiding action is taken, is approximately proportional to the square of the traffic density and directly proportional to the size and the speed of the craft."

According to Hargreaves (1973):

> "The waters from the Elbe to the Western Approaches of the Channel account for over half the world's collisions"

The Dover Strait is the narrowest part of the Channel and is further constrained by many natural obstacles such as the Sandettie Bank, the Varne and the Ridge. Its funnelling effect on through-traffic has led to the Strait recording more collisions and strandings than any other area around the British Isles. Figure 1.2 shows all such occurrences for the 16 year period from 1960 to 1976. The risk of danger and the hazards of pollution and contamination influenced the Governments of the United Kingdom and France in taking special measures to attempt to bring some order to the otherwise random nature of the traffic.

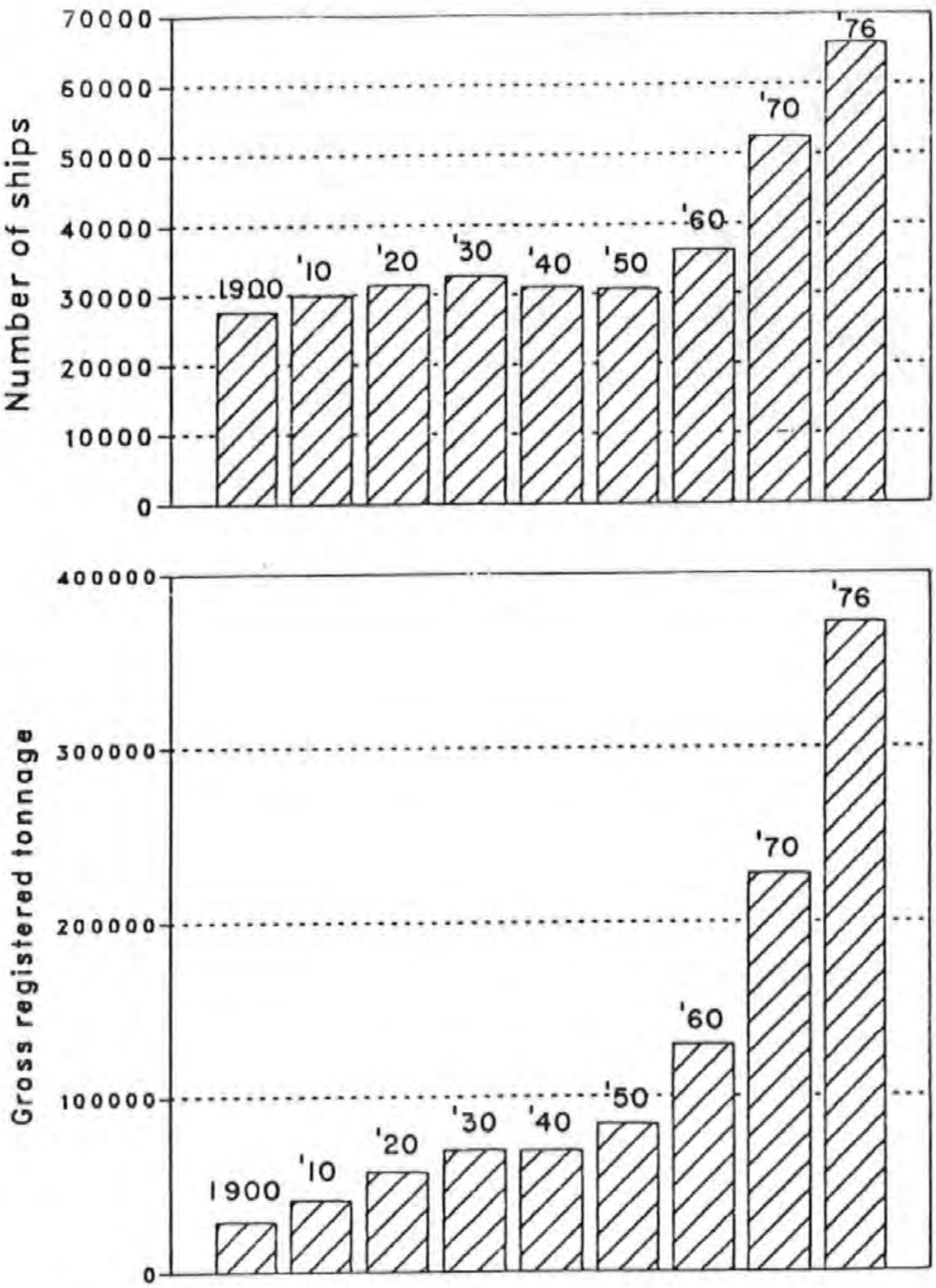


Fig. 1.1 Growth of world shipping

1.2 The results of Traffic Separation

1.2.1 The advantages

Appendix A shows a chronological list of the major developments both national and international, in the subsequent improvements of the Channel. One result of this co-operation has been the establishment of a Traffic Separation Scheme (T.S.S.) through the Dover Strait. The original objective was simply to separate the traffic and hence reduce the number of head-on encounters. Table 1.1, illustrates the success of the T.S.S. in this respect.

Table 1.1

Success of Traffic Separation 1967-74
Worldwide in Traffic Separation Areas

Period	Collisions Between Meeting Vessels	Other Collisions
1959-66	264	160
1967-74	115	160
Reduction	56%	Nil

Source: Cockcroft (1976), Statistics of Collisions at Sea

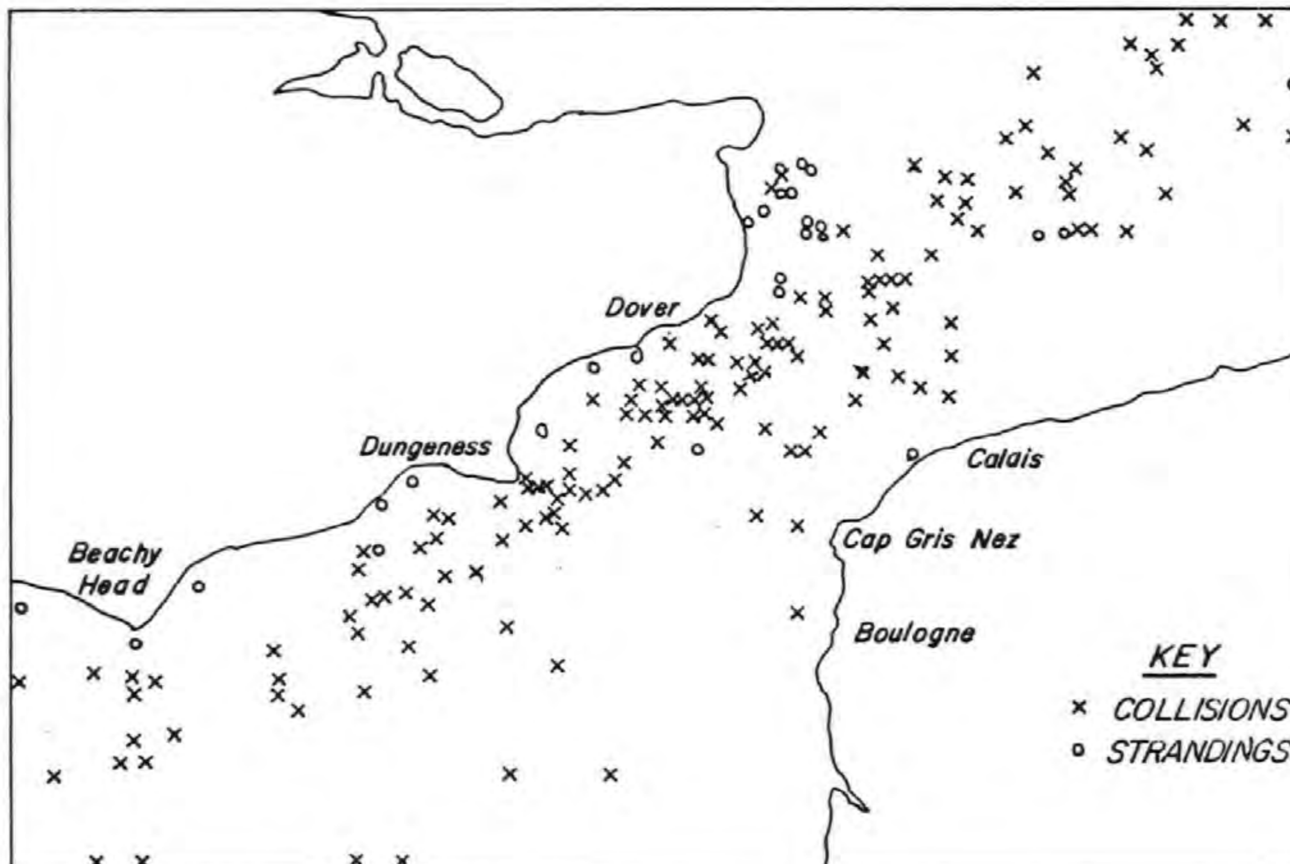


Fig. 1.2 POSITIONS OF COLLISIONS AND STRANDINGS 1960 to 1976

1.2.2 The disadvantages

1.2.2.1 Overtaking

Although it has been shown clearly that the number of head-on encounters and hence collisions have been reduced, the problems of collisions between crossing and overtaking vessels in T.S.S.s have yet to be solved. With the reduction of the head-on encounter, however, was an increase in the number of overtaking, crossing, and to some extent, converging encounters, from the pre-routing scheme level. The proportion of potential overtaking encounters, in the Dover Strait, increased from 27% to 95% (Curtis, 1977). Emden (1979) indicated that

> "..three out of four cases of collision, which took place in the Dover Strait in 1978, were the result of overtaking encounters."

Curtis (1977) set a standard for determining the minimum track separation between overtaking vessels in poor visibility, based on the minimum time required to avoid collision given a sudden alteration across the bow by the overtaken vessel. An analysis of the traffic navigating through the Dover Strait has shown that, according to Curtis, the mariners are not leaving enough room, suggesting that the number of overtaking collisions should be higher. Cockcroft (1981) suggested that the reasons that there had not been a proportional loss of vessels in overtaking encounters was:

> "...due to the increased vigilance of the watchkeeping officer and, possibly, to the presence of the master on the bridge."

The increased attention required, however, in transit is not desirable leading to a possible increase in stress and tension through the voyage.

1.2.2.2 Crossing

A major change to the 1972 Collision Regulations was the introduction of Rule 10c (Appendix B), requiring vessels to cross routing schemes at right angles. Its validity has been challenged by mariners and in particular ferry masters, whose average journey time has been increased as a result. Research has taken place to consider the optimum angle at which to cross T.S.S.s with Lewison (1978), Barratt (1973), Lamb (1979) and Kwik (1979) all making valuable contributions. The conclusion being that, for a single lane, a course set at an angle in the direction of the main flow reduces the number of encounters. For example a crossing of 50 degrees compared to that at 90 degrees, reduces the encounter rate by 18% for 12 knot crossing traffic, and by 12% for 18 knot crossing traffic. It was shown however that when crossing both lanes (running in opposite directions) the minimum encounter rate, for a single heading, occurred with an angle of 90 degrees.

1.3 The risk of catastrophe

1.3.1 The ship's size

The size of ships in transit through the Dover Strait has increased dramatically since the 1939-45 war. Figure 1.3 illustrates the growth in world shipping for three ranges of dead weight tonnage (d.w.t.).

It shows how the greater than 10,000 d.w.t. group has increased by nearly 800% from 1948 to 1975. The size of the vessel is important for three major reasons:

a) it reduces the manoeuvrability of the vessel;

b) an increase in draught results in a reduction in manoeuvring room in a relatively shallow area like the Strait. Figure 1.4 demonstrates how the draughts of ships have increased since 1900;

c) the increasing hazard from a marine casualty follows from the increase in size of individual ships (Le Pla, 1978).

1.3.2 Noxious cargoes

A feature of the seventies was the growth of the super-tanker or Very Large Crude Carrier (V.L.C.C.) culminating in the introduction of the Ultra Large Crude Carrier (U.L.C.C.). The Anglo French Safety of Navigation Group (A.F.S.O.N.G.) observed in their 1977 report that there were 19 oil-tankers entering and leaving the Strait per day, with 2 in each direction of over 200,000 d.w.t. Although the oil tankers account for approximately two thirds of the total tanker fleet, there are still a substantial number of gas, chemical and ore/bulk/oil carriers navigating through the Strait every day. Any of these vessels, involved in a collision might produce a result ranging from a hard financial blow to the devastation of the surrounding coastline and the local marine life. The results of the "Amoco Cadiz" are difficult to forget, but what of the effects of a floundering chemical tanker carrying anything from sulphuric acid to spent nuclear waste. Indeed this has been demonstrated recently with the loss of

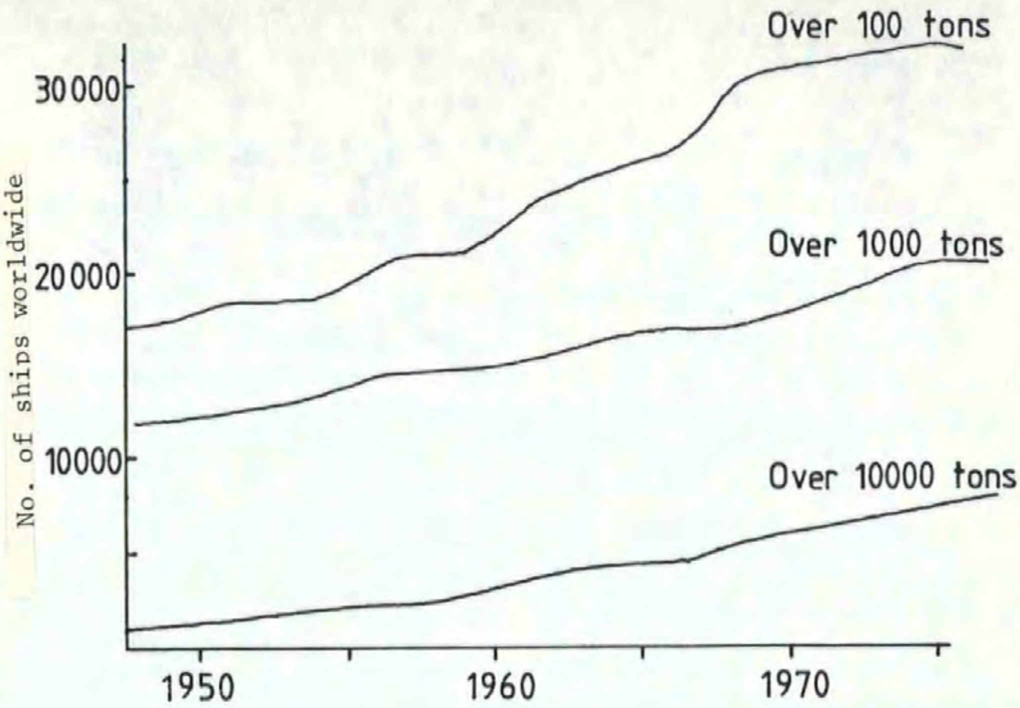


Fig.1.3 The growth in world shipping for three ranges of tonnage

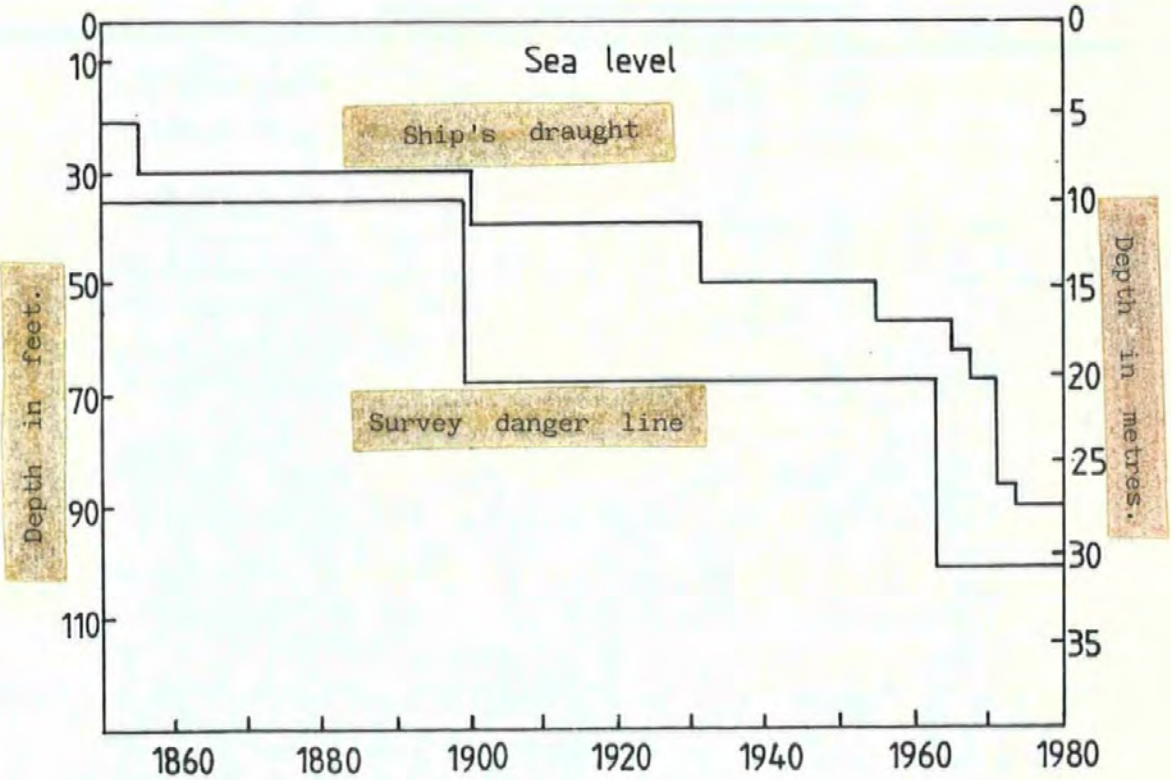


Fig.1.4 The increase in ships draughts since 1900

canisters containing radioactive uranium hexafloride, following the collision between the 5800 dwt. "Mont Louis" and the 15000 dwt. ferry "Olau Britannia" off the Belgian coast, on the 26th. August, 1984.

1.4 The results of compromise

An intrinsic problem in the natural process involved in the design of any system requiring national and international co-operation is that it will, on completion, reflect a compromise of interests. The possibility of pollution or contamination through spillages or collision resulted in the conservationalists advocating that carriers of noxious substances be kept at the maximum possible distance from the shore. This idea was evident in the French routing scheme off Ushant, following the devastation of the coast of Brittany from oil pollution, due to the loss of the "Amoco Cadiz". Clearly the port operators, shipowners, government and, the most important of all, mariners all have a preconceived ideal relating to the design of the routing scheme.

1.5 Independent assessment

It has been shown above that although the Dover Strait T.S.S. has reduced the risk of collision, it has not been to everybody's liking. It has been argued further that, with the vessels now operating through the Strait, even the present level of casualties is too high. Solutions have been put forward: Abdulgalil (1978) suggested the use of a lane dedicated solely to carriers of potentially dangerous cargoes or a separate lane for slow vessels. Changes to the Collision Regulations have been considered, in particular relating to the concept of co-operative manoeuvres, with both vessels contributing to the resolution of the encounter (Calvert, 1960). Clearly the requirement is for a means of investigating different systems or changes to the existing system. The aim of this research is the construction of a computer simulation, that models traffic flows through the Dover Strait. Through its method of construction, which consisted of concentrating on simulating accurately mariners' actions in a manoeuvre and then building up to include navigation and the identification of different ship types, the model has the flexibility to consider such variations to the system.

The availability of an accurate simulation of the area would have enabled an evaluation of the different possibilities for the design of the system, at a low cost and without the normal consequences of failure. Although its prime function is to determine the efficiency of a system through the numbers of encounters and other simple derivatives, these could be combined with the ships types and positions and from Lewison's work on the probability of an encounter leading to a collision, an estimate of the corresponding economic and environmental losses determined.

The model has the potential to act as a decision support system to any future traffic surveillance service that might operate in the Dover Strait. Such a model might provide information to personnel to decide on the best traffic management measures in the event of routine reorganization or disaster partially blocking the scheme.

1.6 The history of the research

In 1978 Davis (1981) started his programme of research into the accurate modelling of ship encounters. His model aimed to expand other more simplified simulations, in particular those of Batkin (1976) and Degré and Lefèvre (1978). Although Degré and Lefèvre (1981) expanded further their system to be able to consider the advantages and disadvantages of different traffic systems, their model and that of Batkin did not have the facility to allow vessels to make collision avoidance manoeuvres. The research by Davis was in collaboration with the Marine Traffic Research Unit, City of London Polytechnic and the then National Maritime Institute at Feltham. Over a period of three years Davis was succesful in developing the concept of the domain as a means of determining whether a vessel was threatening own-ship. He introduced the concept of the arena as a means of evaluating at what point a vessel was threat ening and established a set of algorithms, which were implemented in Fortran IV, by which any necessary action was executed. The program which was developed initially to control the action of vessels following the Collision Regulations in good visibility was ultimately developed to control up to six vessels both in open water and in the vicinity of a coastline.

The initial aims of the present research were to increase the number of vessels that could be controlled by the computer simulation, to implement a stochastic variation in mariners' reactions and to develop algorithms to navigate vessels through narrow Channels. Through the course of the research however some of these aims were rejected, some were modified and some were enlarged upon. The first stage in the research was to re-examine the basic principles of the domain and the arena. This took the form of a conceptual re-evaluation and a substantial analysis of available data sources. The result was the development of multi-circular domains and the Range to Domain over Range-Rate (R.D.R.R.) concept. Further research revealed inadequacies in the program developed by Davis and as a consequence the two models described above were incorporated along with original manoeuvring algorithms into a new computer program.

Subsequent developments were the ability of the model to control more than 400 vessels over a period of two days and the incorporation of a means of navigating vessels though the Dover Strait. Further work included the simulation on a colour graphics terminal of a radar display. This allowed a mariner to control one vessel in a realistic situation with computer controlled targets. Although not in the initial development plan this was thought to be one of the most promising uses of the computer model.

1.7 The present work

The difficulty in attempting to model the mariners' encounter-manoeuvre system is explained in Chapter 2 and in particular the difficulty in attempting to quantify an average mariner's actions. The varying sources of data are discussed and evaluated and the manner in which they were analysed have also been considered. The manner in which mariners follow the Collision Regulations in collision avoidance is then considered in detail.

Chapter 3 considers the development of the domain and the arena. It looks at the problems encountered in their use in the computer simulation and the subsequent reasons for rejecting them. The development of the multi-circular domains and the R.D.R.R. concept is subsequently discussed in detail.

The collision avoidance algorithms used in the open water situation are considered in detail in Chapter 4. This involves analysing mariners' actions in open water situations, following the natural progression from the initial detection, to the alteration of course and concluding with the eventual altering back onto course.

Chapter 5 discusses the difficulties experienced in modelling a continuous dense flow of traffic, and shows how they are overcome by realistic modifications to the encounter methodology.

The ultimate stages in the computer simulation of an existing area of sea are discussed in Chapter 6. These include the manner in which vessels are navigated through and across the Dover Strait, the avoidance of land and buoys and other problems associated with individual ship types.

The main validation of the computer simulation is considered in Chapter 7. This consists in essence of a statistical comparision between results from simulation runs and observed results. The essential comparisions are between the numbers of encounter and the spatial distribution of these encounters, the distribution of Closest Points of Approach and the lateral distribution of through traffic on exit from the simulated area.

The uses of the computer simulation as a decision support aid are shown in Chapter 8. These include the ability to predict the results of both through and crossing rogues, the relaxing of Rule 10c, the effects of a partial blockage of the main lane and the results of a possible further increase or decrease in traffic density.

The development of the computer simulation of the radar simulator, initially as another means of validation and then as a valuable tool in its own right is described in Chapter 9. It is shown how the complexities of presenting all the standard information to the mariner are solved. The problem of providing a visible represention of targets so as to be in the position of claiming good visibility conditions is also considered.

Chapter 2 The Mariner-Encounter-Manoeuvre System

2.1 System Variability.

There is a variability in the shipping system that suggests that no two mariners will resolve a similar conflict in the same fashion. The most obvious reason for this is that no two mariners are identical and as a consequence each has his own preferred course of action in any particular situation. To quote Bury (1977)

> "...the navigation of a ship is an intensely personal affair...".

Training is to some extent a leveller of individuality, attempting to standardize reactions to different patterns of encounters. A more significant factor however is a mariner's experience. Experience is important in two ways: firstly, experienced mariners are less likely to pass dangerously close and hence less likely to spend unnecessary time increasing their miss distance if already at safe distances (Curtis, 1980) and secondly, a long period on one type of vessel, as is often the case for a mariner employed with a container, oil or ferry company, can result in a familiarization with the vessel and its responses and requirements in any situation. Thus the actions of the experienced mariner are often noticeably different from those of his less experienced colleagues. Brough and Jones (1970) conducted a survey of 700 mariners, by questionnaire, as an investigation into the ways in which radar was being used, their findings emphasized the variation in performance over the spread of respondents.

The differences in the reactions of experienced mariners from those new to the sea and implicitly with recent training are not as great as they might once have been. Over the last two decades the introduction of the radar training simulator has substantially reduced these previously unavoidable dissimilarities in practice and skill. It has allowed inexperienced mariners to take command of a simulated vessel in a safe, relatively realistic atmosphere, under the guidance of a skilled instructor. There are many who might doubt the authenticity and value of a radar simulator training course to the education obtained at sea. It was, however, never intended that simulator training should replace experience at sea, but that it would prove a valuable complement and a means of gaining an initial degree of competence. To quote Paffett (1981)

> "Sooner or later in every discussion of simulators with seamen the point is made that 'you can't teach real seamanship on a machine - the only way to learn about the sea is to go to sea', and so on. To which the response must be made at once that the advocate of simulation will not pretend that it is a complete substitute for sea experience, but he will claim that it is a most valuable supplement to, and preparation for, sea experience.".

Clearly, since simulation increases the number of experienced mariners then it should also reduce the variability of actions in the shipping system. The development of the ship-handling simulator, particularly over the last decade has been further instrumental in the reduction of the variability of actions. In particular it has allowed mariners to become familiar with a particular type of vessel's manoeuvring characteristics before sailing. To quote Zade (1978):

> "...training in simulators should be offered to nautical officers presently serving on large and unusual ships. Even the mariners who do not intend to serve on large and unusual ships will benefit by an abridged ship-handling simulator

training if they sail in waters where these vessels are likely to be encountered. A simulator course will increase their capability to assess the features and limitations under which large and unusual ships have to proceed.".

Conventional training attempts to reduce the otherwise random nature of mariner's reactions through the provision of a rigid structure of procedures. Procedural definition is in the form of the International Regulations for Preventing Collisions at Sea (the Collision Regulations). It might be thought that such an internationally applied code of conduct would reduce to negligible proportions the variation in actions and hence diminish the number of collisions normally due to misunderstanding. The Collision Regulations are however subjective in their approach to distances and times in collision avoidance. For any two vessels involved in an encounter, at least one will be assigned a give-way status from the geometry of the situation. No unique definition is made, however, in the rules as to when that status is to be fixed. This is of particular relevance when a mariner observes a target on a slowly converging course on his starboard side (Fig.2.1). If the two vessels are not on a direct collision then the sight-line will rotate. This means then if the target (B) is initially, at time t=t1, on a bearing greater than 22.5 degrees abaft the beam and passing slightly ahead, that it is initially overtaking own-ship and own-ship is stand-on. If, however own-ship is a little later, at time t=t2, in attempting to determine its status with respect to the target then the target could now be on a bearing less than 22.5 degrees abaft the beam and consequently own-ship would now be in a converging crossing situation. Thus a difference in the time at which a mariner fixes effectively the status of his own vessel, relative to a target, can result not only in a different manoeuvre taking place, but in no manoeuvre being executed at all.

Another situation in which human variation can result in a difference of action is when two vessels are approaching head-on and starboard to starboard (green to green). In such an encounter one mariner might conclude that no threat of collision exists but that a slight alteration of course to port would increase the miss distance to a more acceptable level. Yet in exactly the same situation another mariner could feel that a real threat of collision exists and as a result the Collision Regulations apply and an alteration of course to starboard would follow.

Kemp (1972) compared the actions of mariners (experienced subjects) and non-mariners (naive subjects). The comparisons were conducted on the City of London Polytechnic simulator, using a series of standardized encounters. Figures 2.2a to 2.2d show the different responses between the experienced and the naive subjects. Figures 2.2a and 2.2c both illustrate unambiguous situations, resulting in the experienced mariners, who were following a set of rules, behaving in a more uniform manner than the naive subjects. Both figures 2.2b and 2.2d show encounters that were designed to be ambiguous, their interpretation, according to the Collision Regulations, being purely subjective. In these two situations, it can be seen that the naive subjects were much more predictable in their actions than the mariners. Kemp's conclusions were as follows:

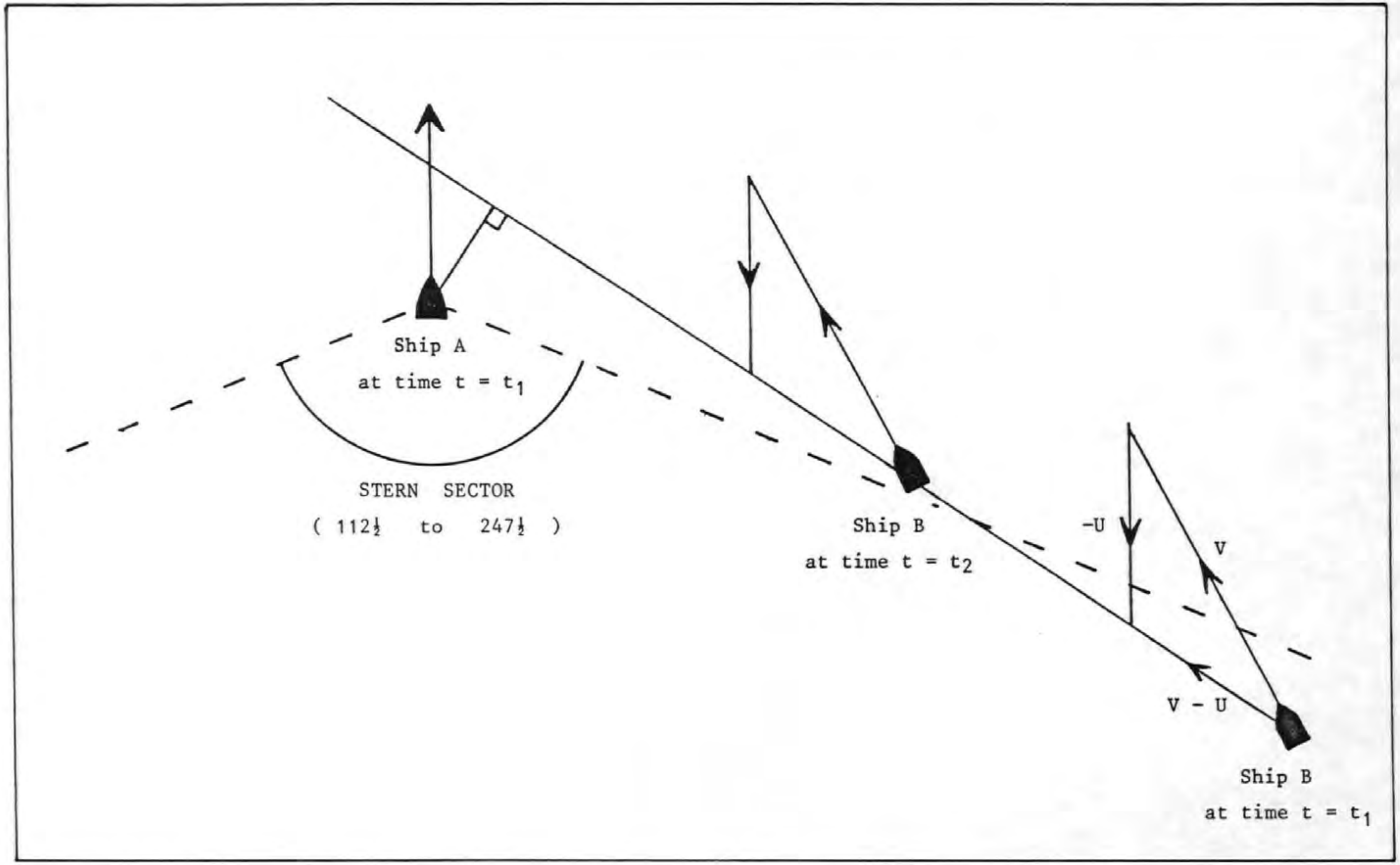


Fig. 2.1 The variation in ship's status over a period of time

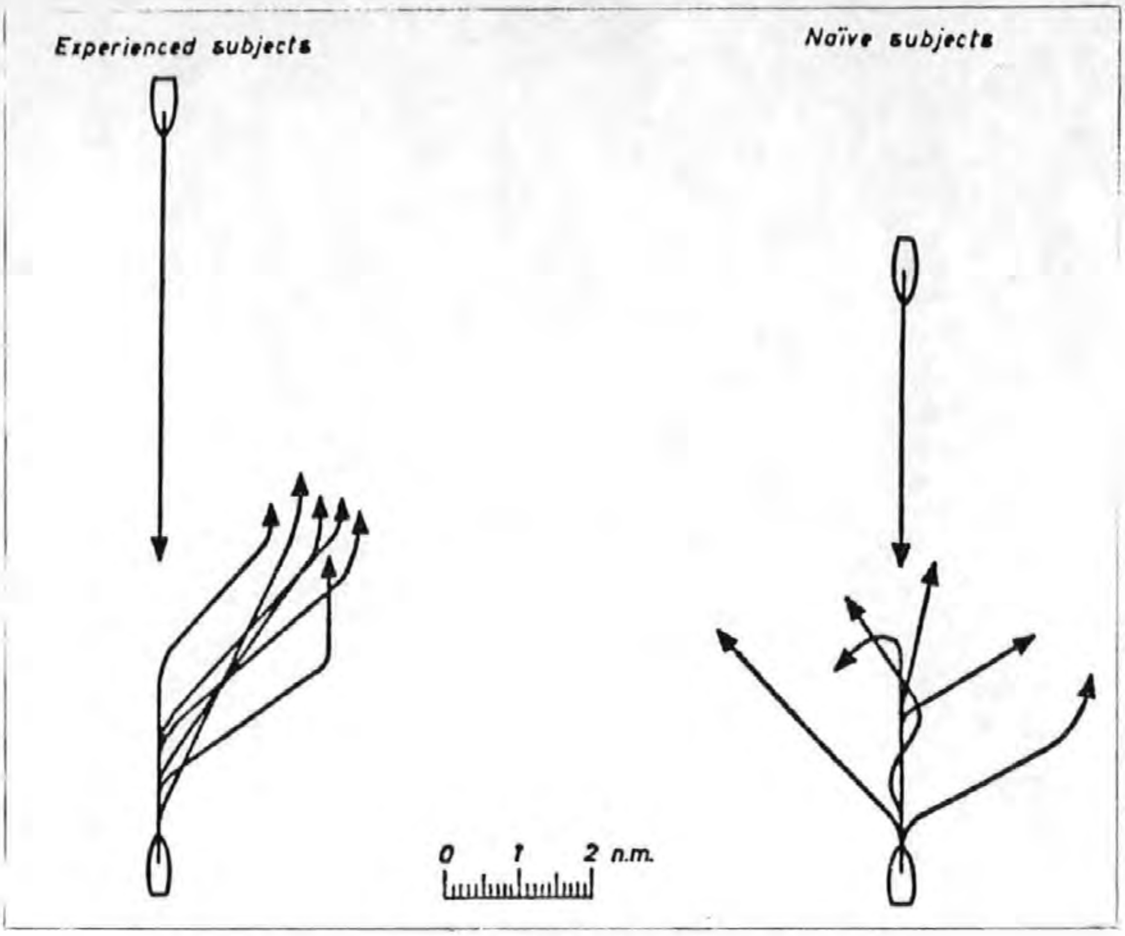


Fig.2.2a Typical action in a head-on encounter

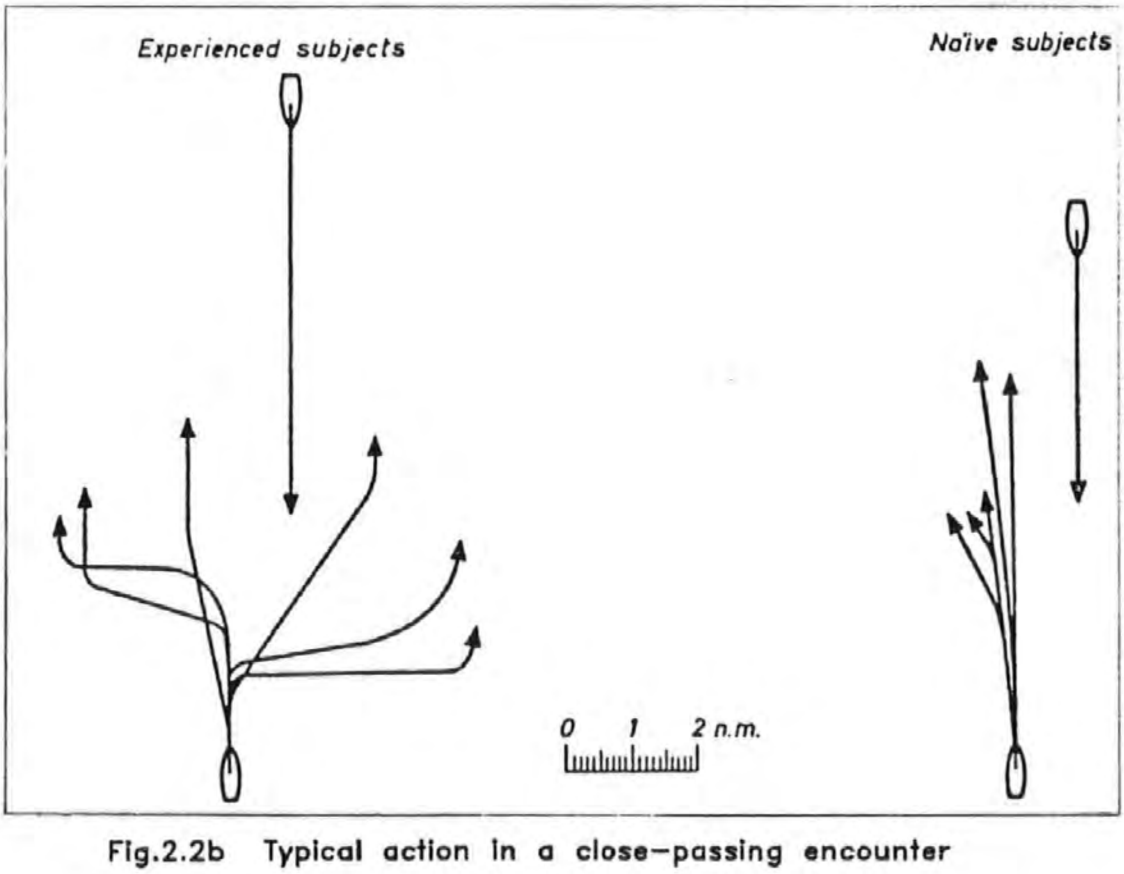


Fig.2.2b Typical action in a close-passing encounter

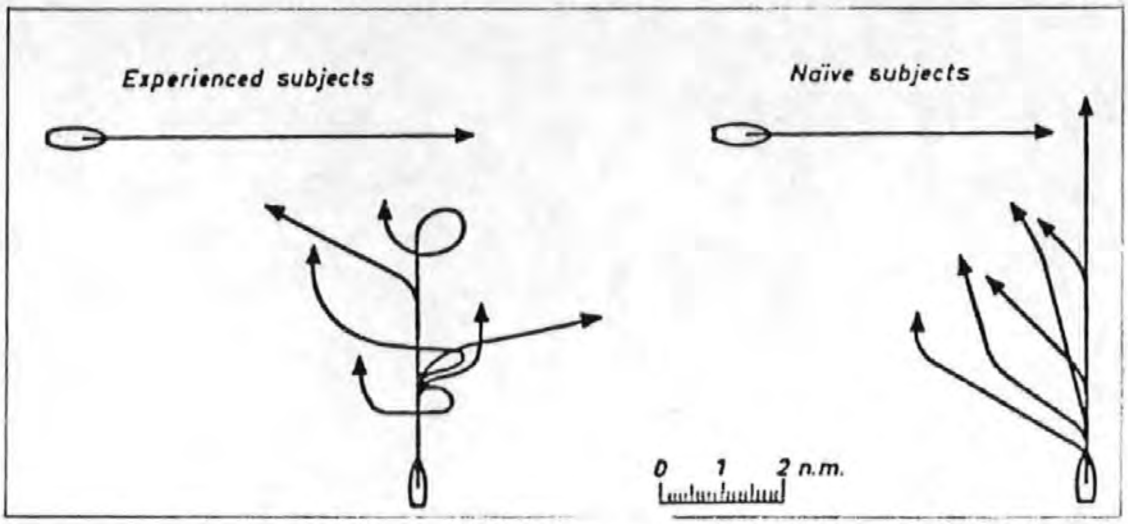


Fig.2.2c Typical action in a crossing encounter from the starboard side

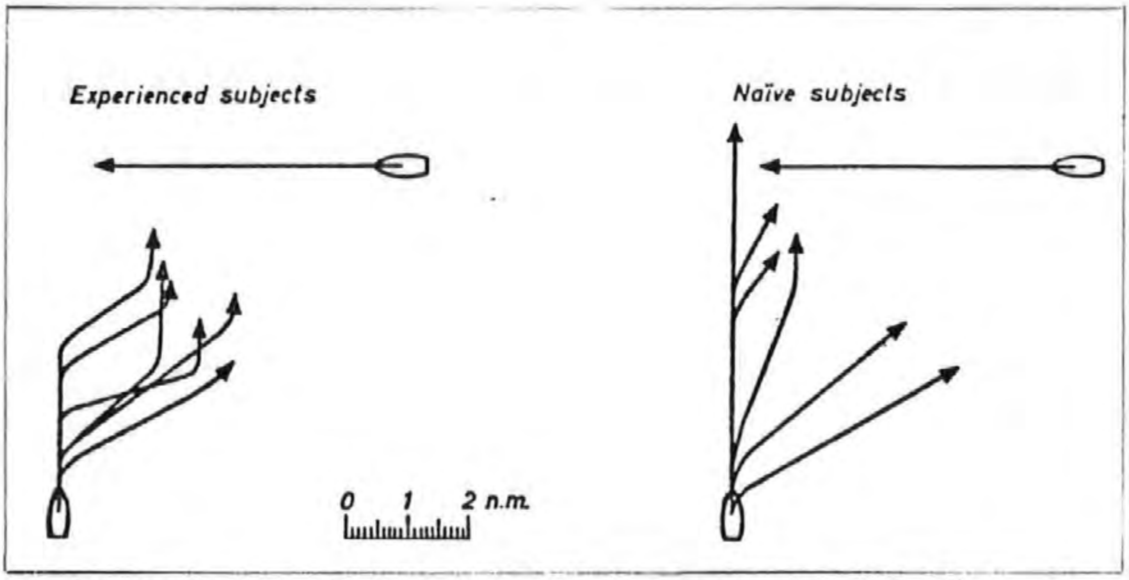


Fig.2.2d Typical action in a crossing encounter from the port side

> "This study has defined some situations in which mariners take inconsistent and therefore unpredictable action. It is suggested that the Collision Regulations might actually sometimes create this inconsistency..."

There are other factors that can change the same mariner's response to the same geometric conditions at different times. His threat threshold may be reduced as a result of being rushed to make the tide or to meet some other dead-line. His company might be applying stringent economy measures and consequently cutting down on his ability to make large manoeuvres off the track, resulting in time being wasted. Finally a mariner is only a human being and as such suffers from stress, especially when coming from deep sea into a heavily trafficked strait.

In constructing an algorithm to model mariners actions, some form of rationalization of mariners' actions was required. For the purposes of this research an initial hypothesis was made that there existed an average mariner. The concept of the "average mariner" does not describe any particular type of mariner, but attempts to standardize the observed distribution of actions and reactions in such a manner as to model most accurately the observed shipping system. Random decisions as to the type of manoeuvre to be executed and the statistical distribution of what miss distance constitutes a threat will be discussed later.

2.2 Sources of Data

It can be seen that some means of quantifying the mariners' actions and characteristics is required. As shall be seen later, hypotheses may be made concerning likely mariners' responses to known situations, but there must be some foundations to such reasoning apart from that which seems intuitively obvious. There exist two approaches to this vital collection of facts and data. The first is a qualitative approach, in which mariners' advice is sought and assimilated for subsequent use where relevant. The second is the quantitative approach in which some form of numerical data can be collected and analysed statistically in order to gauge underlying trends. The practical combination of these two data acquisition methods has led to the generalized practice of talking initially to experienced mariners to gauge the course of action that should be followed and then reinforcing this with a statistical analysis of the data relating to the mariners' reactions.

The detailed qualitative information was available in three forms: literature, verbal conversation and observations in the field. The Polytechnic, with its strong maritime connections and support of only one of four degree courses in Nautical Studies in the country, had a large supply of relevant literature. Furthermore its professional mariners' courses meant that not only were there many ex-mariners now lecturing, but there was also a large number of mariners still at sea. Finally and perhaps the most important means of acquiring information of quality was via the two studies in the field. The first involved a return crossing by ferry, courtesy of P & O Ferries, from Dover to Boulogne. The second study consisted of a transit of the main north-eastbound lane, from Southampton to Hamburg by container vessel. These two trips were both of great importance because although no quantitative data could be obtained, in both cases the author was permitted to observe without interruption and on request was given helpful information.

There were three main sources of quantitative information available to the research: the radar film; the radar simulator exercises and the questionnaire. The advantages and disadvantages of each are discussed below.

2.2.1 The Radar Film

The main source of data used in this research was the radar films. These were high quality, 16mm. films of one of the operating radars at H.M. Coastguard Station at St. Margaret's Bay, made by a team from the Department of Trade and Industry, National Maritime Institute. Copies of several 12 n.mile and 24 n.mile radar films were kindly provided. In general the 12 n.mile (the total diameter of coverage) films were used for the detailed work involving the extraction of manoeuvring or initial condition parameters in an encounter (C.P.A., T.C.P.A., distance apart etc.), whilst the 24 n.mile film was used to look at variables relating to the system as a whole (most used routes, spatial distributions etc.). For the detailed analysis it was decided to use the most recently obtained 12 n.mile film, which covered seven full days traffic during March 1981. Ship tracks were plotted over a continuous period of ten hours and an analysis carried out to determine mariners' actions in encounter situations. After analysing the continuous run it was decided that this was an inefficient method, since only a few encounters were perceived each hour. A better method was simply to record encounters when observed. In this manner a data set of 210 encounters over a period of six days of good visibility were obtained.

Data recorded at the time that a vessel was about to alter course included:

a) the date and time;

b) the initial Closest Point of Approach (C.P.A.);

c) the Time to C.P.A. (T.C.P.A.);

d) own-ship's course and speed;

e) target's course and speed;

f) relative bearing of target;

g) course difference between target and own-ship;

h) distance apart.

Details concerning the manoeuvre were:

i) the angle of alteration;

j) the New C.P.A. when own-ship had stopped altering;

k) relative bearing and distance apart when own-ship was about to alter back onto course;

l) the Actual C.P.A. observed.

2.2.2 Radar Simulator

Plymouth Polytechnic has two radar simulators. The simulator used in all cases for the experiments was the Redifon C 8012. The exercises used were given to mariners undergoing their professional Electronic Navigation Systems course, and was comprised mainly of mates and First officers. The simulation area used for the analysis was the Dover Strait. The exercise involved three vessels steaming down the Main South-Westbound lane of the routing scheme and several ferries crossing from either side. Since the exercise was set up so that the mariners were likely to be required to take some form of action, a large source of manoeuvring data was available.

A further simulator exercise was specially constructed and consequently, with the help of Captain W. Brown, set up on the simulator. The aim was to provide high quality data on overtaking encounters. This was necessitated because of the difficulty found in obtaining valuable information on overtaking situations from the radar film. The main difficulties involved in the radar film analysis were:

a) the small relative velocity between two vessels involved in an overtaking encounter. The result of this was that due to the length of time needed to cover the total encounter, the whole encounter was seldom completed over the length of the displayed section of routing scheme. It was not possible to move up to the 24 n.mile range because of the markedly reduced accuracy;

b) since the film only covered the routing scheme and not the area in which the vessels initially entered the scheme, it was felt that many of the vessels had already manoeuvred to come into a formation in which to navigate the strait.

The major advantages of the simulator were:

a) that the same initial conditions could be repeated for every exercise. This meant that different mariner's actions to the same initial conditions could be obtained. For this reason simulator results proved useful in looking at the stochastic variation in mariners' reaction times;

b) the absolute accuracy of the positions and hence the accurate assessment of course, speed etc.;

c) the background data from which professional information on those involved in the exercise could be obtained;

d) the delay in the response of a vessel to a change in the rudder lead to difficulties in attempting to determine exactly when a mariner first puts the helm over. The simulator incorporates realistic ship dynamics and while there was a delay in the ship's response to the helm, it was however, possible to observe the exact moment at which the mariner altered course;

e) the ability to obtain the exact time at which a mariner ordered a change of speed remained an impossible task from the radar film. This was due to the time required to gauge a vessels speed using a manual plotting method (no less than three minutes). Thus an approximation of when a vessel did alter speed, if the change was observed at all, could be no more accurate than 1.5 minutes. The change in speed could however be ascertained easily with the simulator run; either from the subsequent graphical output (x-y plot) or from the subsequent debriefing.

One of the greatest limitations of the use of results from the radar simulator as data for the simulation model was that it is always defined as running in "bad" visibility. The simulation had been conversely defined as obeying the normal rules for good visibility and furthermore used data collected from good visibility sources. Chapter 9 discusses the construction of a computer model capable of simulating the characteristics of a mariner's Plan Position Indicator (P.P.I.) and also providing a clue to the aspect of the targets and hence an approximation to the good visibility situation. It was hoped also that some use might be made of one of the ship simulators in operation in the U.K. as a means of obtaining good visibility manoeuvring data. The author approached those in charge of the Cardiff ship simulator and the Warsash ship simulator and after a reply from Cardiff and a visit to view the simulator at Warsash, came to the conclusion that no relevant data was available. The reason for this was primarily because the main role of the ship simulator is in the handling of large or difficult vessels in port approaches and hence little was available on the Dover Strait or even deep water exercises.

2.2.3 The Questionnaire

The last means of collecting data was via the questionnaire (Appendix C). A questionnaire was carefully prepared, which was then presented to students attending the radar simulator course. Since the author was attending the same course it was decided that he should remain anonymous to the respondents and the questionnaire was subsequently distributed by the lecturer in charge for immediate completion. It was stressed that any personal information would be treated in confidence, the aim being to restrict "safety first" replies to the questions. It was felt however that the use of the questionnaire as a reliable source of information was dubious for the following reasons:

a) the way in which the majority of participants treated the questionnaire as a test, which even though remarks concerning anonymity were included at the beginning, meant that actions were generally over cautious;

b) the difficulty in constructing the questionnaire so as to concentrate the mariner's response to the required area, without influencing his decision. This was particularly noticeable when attempting to determine the criterion adopted by the mariner in determining the time to alter course. It should be noted that the questionnaire was developed and utilised before the Range to Domain over Range-Rate concept (Chapter 3) had been conceived.

After the mariners had completed the questionnaire, they were invited to make a critical assessment of its validity. The major criticism was that they had great difficulty in seeing the encounter develop in their minds, rather than practically at sea (or simulator). They also stressed the problems they had in approximating the distances and times. As a result it was decided that although some 15 respondents had completed the questionnaire that no significance would be placed on the results and that the use of a questionnaire in this type of information assessment was not applicable.

2.3 The Encounter-Manoeuvre System

It was decided that the computer simulation of the encounter-manoeuvre system should be as realistic as possible. Thus from an initial identification of the thought process of the "average" mariner, it was hoped to model the consistent aspects of this particular control system. The addition of human errors such as the misreading of a particular situation or the misinterpretation of another vessel's actions were not included since it was hoped to model the ideal situation. This control system was considered initially for two vessels, in good visibility, and was to be split into three main sub-sections:

a) target detection and categorization of encounter type;

b) threat calculation and assessment;

c) the subsequent action (collision avoidance manoeuvre) or non-action (stand-on).

The initial detection of a vessel was said to occur when the vessel first appeared on the radar screen or P.P.I.. ~~and from simulator experiments for the Dover Strait this was found most frequently to be the six miles range.~~ If the assumption was made that the mariner instantaneously plotted the target's track as soon as its echo first appeared, then the status of the own-ship with respect to the target could be said to be determined as soon as the vessels had been inside that range for at least three minutes. A further assumption was made that no vessels were restricted in their manoeuvring capability (special cases in the Collision Regulations - Rules 27 and 28), and consequently the status could be determined by the relative positions of the two vessels with respect to each other, the course difference and the absolute speeds of the two ships.

The next stage in the process was the determination of the existence of threat from the vessels under observation. This was normally facilitated, for the mariner, through the use of the relative motion display, and consisted of an extention of the target's relative track and the measurement of the length of the perpendicular to that track from the own-ship. This gave the Projected Closest Point of Approach (P.C.P.A.) of the two vessels or the C.P.A. if neither of the vessels alter course and/or speed. It is from the P.C.P.A. that the mariner then gauged whether a threat existed or not. Thus the assumption was made that the average mariner had some pre-determined criterion of safety against which the judgement of threat was ascertained. If the P.C.P.A. fell below this safety threshold then the target was said to be threatening own-ship.

The final stage of this simplified system was to determine the action taken. This action might have been the decision to alter course, to alter speed or to take no action (stand-on). Since the model represented the decisions that would be made by a competent mariner working co-operatively with any other vessels, then the give-way vessel always manoeuvred whilst the stand-on vessel always took no action. The only exception to this generalisation was in the case of two vessels meeting head-on, in which case under certain conditions both vessels had the facility to alter course. Thus, in the crossing situation, the mariner altered course until the target was on his port bow or, in the overtaking and head-on cases, until the target's relative track was no longer threatening. The mariner made his decision at a fixed time before C.P.A.. Finally he had to decide when to alter back onto course and in practice this proceeded as a small adjustment of course in such a manner as to always keep the target at some minimum bearing on the port bow.

This constitutes the main elements of the encounter-manoeuvre system. The processes described above have, in all possible cases, been repeated in the computer simulation of the mariner's action. The threat threshold value was derived from a concept conceived by Goodwin (1975) and known as the domain, whilst the algorithm for determining the time at which the manoeuvre was executed originated from a well-tested concept in aircraft collision avoidance theory, the range to range-rate ratio, which was developed into the Range to Domain over Range Rate ratio (R.D.R.R.) (Colley et al., 1982).

Chapter 3 The Domain and the R.D.R.R. concept

3.1 Domain Theory

3.1.1 The development of the domain

The concept of the ship domain was introduced to this country by Fujii et al. (1971). Fujii et al. defined the domain as:

> "a two-dimensional area surrounding a ship which other ships must avoid".

The Fujii domain was the result of separate surveys in the channels of Tokyo Bay and the Urage Strait, and was used to determine the traffic capacities of the respective seaways. Goodwin (1975) conducted an extensive survey in the southern North Sea Sunk area and further established the present concept of the domain. Goodwin defined the domain as:

> "the effective area around a ship which a mariner would wish to keep free with respect to other ships and stationary objects".

Both Goodwin and Fujii obtained their domains by measuring the actual density of shipping around a series of "central ships". Goodwin sub-divided traffic by the relative bearing of the target in each case. Thus the dimensions of the domain boundary were separated into three sectors coinciding with a ship's side and stern-lights. Fujii, conversely, determined his domain from three different sets of data, relating to the overtaking, meeting and crossing encounters.

The Japanese and N.E.European domains differed in one more, important respect: whilst Goodwin obtained the relevant boundary as being the average distance from the centre ship at which the density became equal to the ambient density; Fujii used the distance from the centre vessel at which the density reached a local maximum. From Fig.3.1 it can be seen that given the same area of sea, the Fujii approach always results in a larger value than that used by Goodwin. In a later survey Fujii and Shiobara (1974) gave the consolidated dimensions for all encounters as an ellipse; 500 metres by 300 metres. The original domain obtained by Goodwin for the southern North sea was much larger, to quote Goodwin:

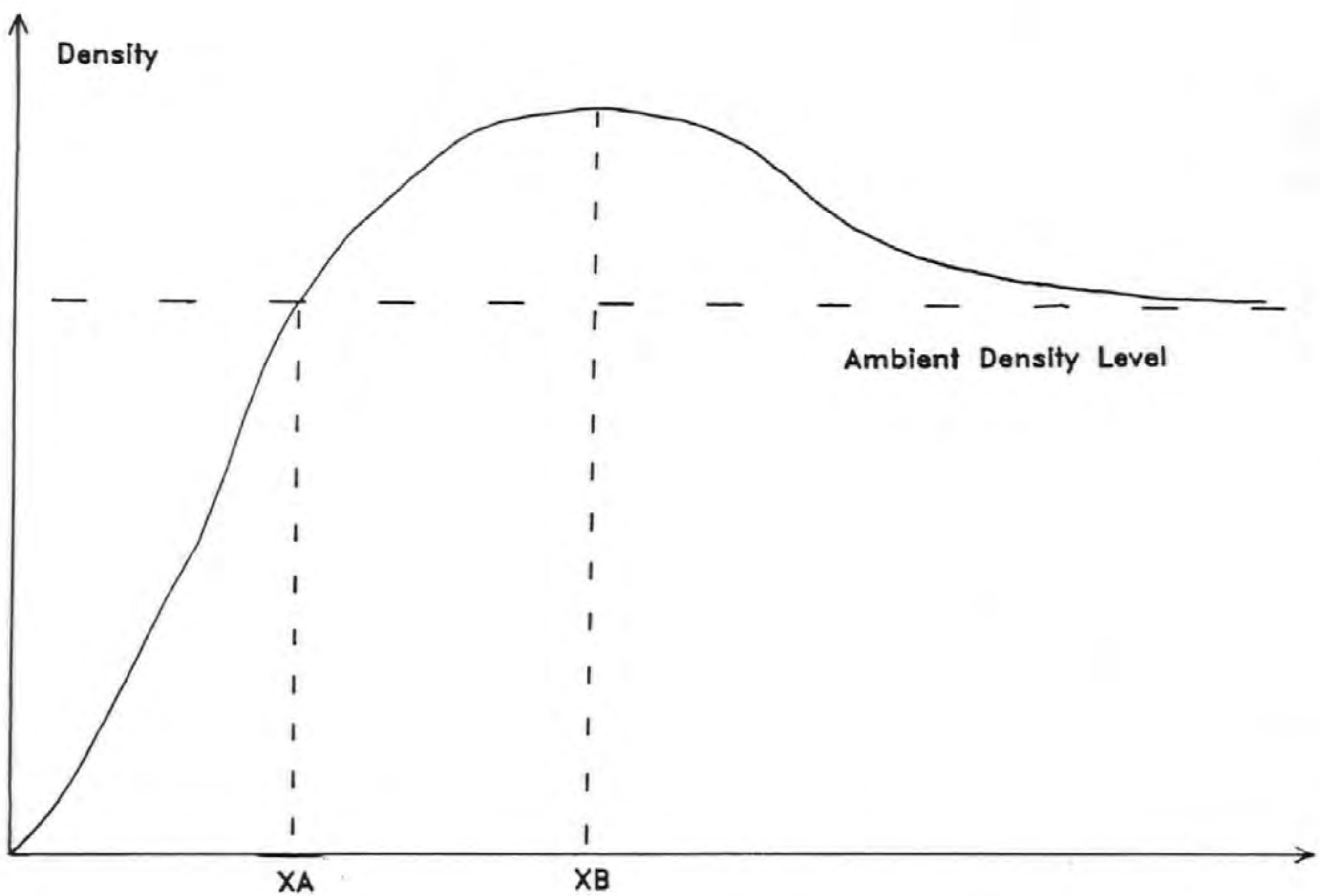
> "...safe distances used by navigators in N.W.European waters are three times as great as those used by navigators in Japanese waters".

3.1.2 The Goodwin domain.

Although Goodwin's original work was concerned with the Sunk area, she also analysed data from other areas around the British Isles. Of particular interest to this research was her analysis of the domain for the Dover Strait (Goodwin, 1978). As might have been expected, from the differences in the two areas, with the Dover Strait having a well established Traffic Separation Scheme and a much more dense traffic flow, the domain obtained for the Dover Strait area was considerably smaller than that determined for the Sunk area. Again sub-dividing the observations into the same three sectors the following values were obtained (Fig.3.2a):

Sector 1 - 0.82 nmiles;

Sector 2 - 0.77 nmiles;



XA – Distance of the domain boundary as defined by Goodwin

XB – Distance of the domain boundary as defined by Fujii

Fig.3.1 The comparison between the Fujii and the Goodwin methods of determining the distance of the domain boundary

Sector 3 - 0.10 miles.

where the sectors are defined as follows:

$0.0 < \theta < 112.5$ starboard sector (Sector 1);

$112.5 < \theta < 247.5$ stern sector (Sector 3);

$247.5 < \theta < 360.0$ port sector (Sector 2);

where θ is the relative bearing of the target ship.

One of the areas in which the new concept of the domain was most successfully utilized was in the development of the mathematical models used to predict the number of potential encounters between vessels. This was particularly reflected in the surge of interest in the modelling of marine traffic systems, in which an emphasis was given to the measurement of the efficiency of the new Traffic Separation Schemes (T.S.S.) which were being established in most of the world's densely trafficked water-ways. The initial attempts at measuring the improvement in efficiency by a comparison of the number of collisions before and after the introduction of the T.S.S. (Hargreaves, 1973) were limited due to the statistical insignificance of the numbers involved. To quote Coldwell (1983):

> "The use of casualty statistics as a measure of marine risk has distinct limitations. In most areas a casualty is a reasonably rare occurence, so that any systematic analysis of casualties will normally have to take place over a period of a few years; and, if improvements are made, a further period of time is needed to ensure their effectiveness."

3.1.3 Uses of the domain concept

The studies progressed then to comparisons of the number of encounters. Draper and Bennett (1972) made the assumption that there was a proportional relationship between the number of encounters and the number of casualties. Lewison (1978) was the first to quantify this assumption when he analysed the risk of a ship encounter leading to a collision in the Dover Strait. Clearly the concept of the encounter as expressed by Goodwin in her work on the domain was different to that used by Draper and Bennett and others in their mathematical modelling. Lewison (1977) defined four distinct meanings to the word "encounter" with respect to marine traffic engineering theory. An encounter was said to occur if:

a) in an actual situation, if no avoiding action were taken, two ships would make a C.P.A. within a given distance;
b) in an actual situation two vessels come within a critical distance of each other;
c) in a mathematical model of an area two vessels come within a critical distance of each other;
d) in an actual situation one or both of the vessels feel threatened by the other and make a collision avoidance manoeuvre.

Following his work on the different types of encounters, Lewison made the distinction between the "domain" and the "encounter area". He considered the "ship domain" to be as defined by Goodwin and hence a measure of the <u>actual</u> density of shipping observed to occur around a ship and the "encounter area" as the <u>desired</u> area that a vessel should try to keep clear. The "encounter area" was clearly the concept used in the mathematical modelling of potential encounters. Draper and Bennett (1972) developed a mathematical model of traffic flow to assess the likely encounter rate in an area of sea for various patterns of traffic flow. An encounter was said to occur when two vessels passed within a specified distance of each other. Barratt and Hewson (1974) counted the number of encounters (definition "b")in the Dover Strait, over a period of time, by noting when two radar echoes merged. They estimated that this represented a mutual approach within half a mile. It can be seen that there exists a clear distinction between the terms "domain" and "encounter area" and that the concept required for this research was the latter. It was decided for the purposes of this research that the term "domain" would be used to describe the "encounter area", since it was still in essence an area of caution around the own-ship.

3.1.4 The Davis domain

Davis et al. (1980) initially used Goodwin's domain in their ship encounter model, but decided that the discontinuities at the sector boundaries were unrealistic and as a result the sectored domain evolved into the off-centred circle domain (Fig.3.2b). Davis hypothesized that if the area subtended by the arc of each sector could be retained by off-centring the ship, then the use of a circular domain was justified. Clearly the distance from own-ship to where the target's relative track cut the boundary of the domain (the domange) was the important factor, since it was boundary infringement that indicated whether or not a target was threatening. The requirement then was for the conservation of the average domange for each sector, but since by definition, the area of each sector is the sum of all the lengths under the boundary curve, then the conservation of area is also the conservation of the average domange, and therefore justifying the Davis hypothesis. This "off-centred" domain was considered to be the most effective single domain for use in a computer simulation of shipping.

3.2 Encounter Theory

3.2.1 Encounter types

A major problem with the Davis domain was its inability to distinguish automatically between different encounters with two targets on the same relative bearing. It was shown in section 2.1 (Fig.2.1) that if a target had a finite miss distance to own-ship, then even on a constant course, its status could vary from overtaking own-ship to own-ship give-way and crossing the target. The test for domain infringement was if the C.P.A. was less than the domange, but since the domange depended solely on the position of the target and the direction of the relative track, then both encounters were regarded with the same degree of threat. Plainly the model needed a domain capable of differentiating between different encounters involving targets travelling along the same relative track. Clearly since the same relative track, regardless of the position of the target, always resulted in an identical interception of the domain, it followed that no single domain had the capacity to recognize such a difference as described above or indeed between a head-on and overtaking encounter with targets on identical relative tracks. The answer appeared to be in the use of a different domain for each type of encounter. It was

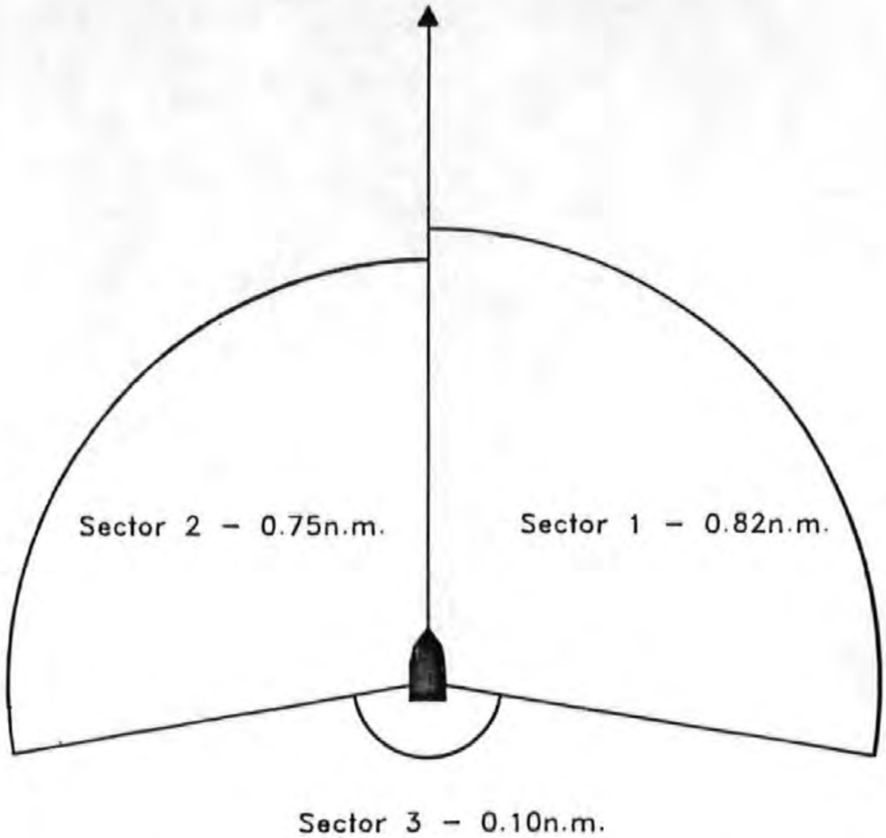


Fig.3.2a The Goodwin domain for the Sunk area

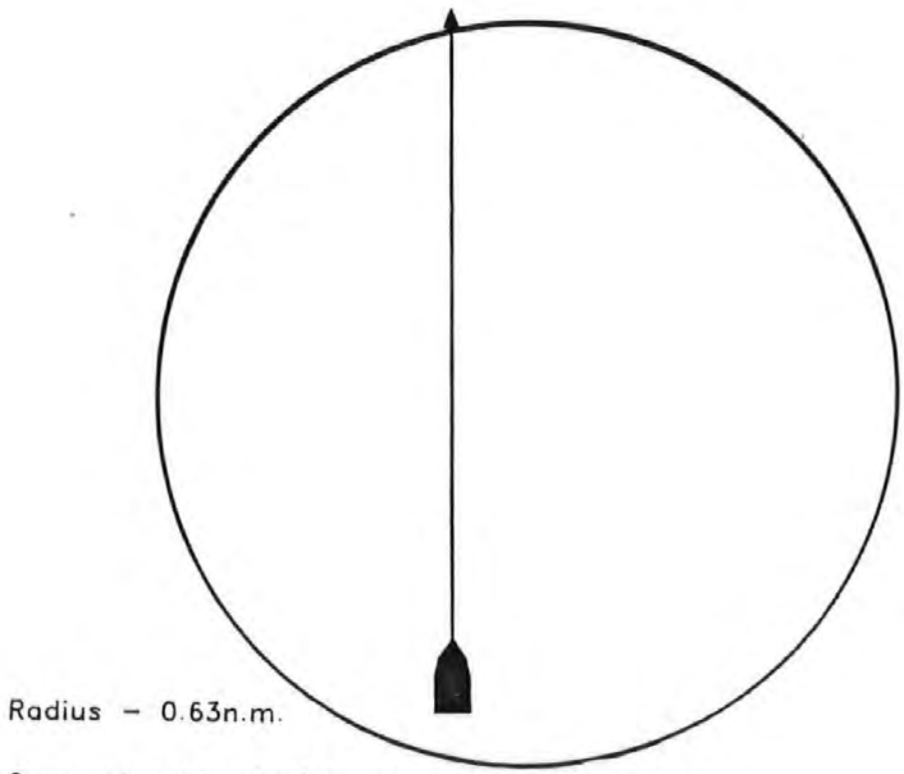


Fig.3.2b The Davis representation of the Goodwin domain

argued that this would result in discontinuities in the mariners' actions, but it was well recognized that mariners adopted different procedures in collision avoidance for different types of encounters. It should also be noted that although Fujii and Shiobara (1974) obtained a single ship domain, the survey was conducted by considering data from separate encounter types in turn and it must be concluded that Fujii and Shiobara recognized the need to distinguish between the different situations.

3.2.2 Stages in an Encounter

It has been suggested above how an encounter was split initially into three sub-sections: target detection and categorization of encounter type; determination and assessment of threat and the subsequent action. Of these stages the initial detection of the vessel and categorization of encounter type did not involve the domain concept. The second clearly encompassed the concept of the domain as described above, that was simply as a means of determining whether or not a threat exists. Finally, although the type of action or non-action was determined by the type of encounter, the mariner manoeuvred in such a way as to reduce the initial threat posed by the target and as a consequence involved the domain to some degree. In the crossing situation, in particular, it was noted that the mariner not only altered course to clear the threat, but altered to a bearing that cleared the stern of the target. This action of manoeuvring further than was absolutely necessary to clear the domain was further emphasized in Rule 8b which stated that:

> "Any alteration of course and/or speed to avoid collision shall, if the circumstances of the case admit, be large enough to be apparent to another vessel...".

Hence although the domain defined the minimum standard for manoeuvring away from a threatening vessel, it did not necessarily determine the magnitude of the alteration. Nor was the decision of when to alter back on to course determined by the domain. It was more likely to be a function of the relative bearing of the target. Hollingdale (1979) quoted Kemp as suggesting that a ship manoeuvres back onto course when

> "...the target bearing has moved further abeam than own-ships initial course".

It was however still necessary to test against domain infringement as it was quite possible for the target to make some unexpected manoeuvre and as a consequence put the give-way vessel back into a dangerous situation. Hollingdale summed up a vessels actions in giving-way in the crossing situation as:

> "a mariner resolves an encounter by turning his ship to face the threat ship (B) and then follows B round in a curve of pursuit".

3.2.3 Restrictions on the use of the Davis domain

It has been shown that the function of the domain, in the simulation, was primarily as a means of determining whether another vessel was threatening own-ship, and although it was possible that the domain was involved in the subsequent stages of the encounter-manoeuvre system it was not necessarily the case. This led to perhaps the most significant criticism of the use of the Davis off-centred circle domain: that it was derived from the Goodwin domain and was, as a result, a model of the data and logic used in the formulation of her domain. Goodwin's domain was by its definition a measure of the actual density of shipping observed to occur around a vessel, where as the concept required of the domain in this research was the desired density of shipping. In more simple terms: the research required a domain capable of determining what should happen in an encounter while the Goodwin domain was a record of what had occurred. Thus the original method, used by Goodwin, in determining the radius of each sector of the domain, resulted in all the stages of the encounter, from the initial recognition up to the eventual alter-back on to course, being included in her domain. This was the precise requirement of her domain since its prime objective was to be a model of the shipping system as a whole. It has been shown above that the only single use of the domain, in the model, was as a means of determining whether a threat existed. It was decided that the whole concept of the domain had to be reconsidered and data analysed to provide the necessary shape and dimensions.

3.2.4 Multi-circular domains

3.2.4.1 Initial hypotheses

Domain infringement could be considered in two ways: firstly, if the domain was infringed at any point by the relative track of a target and secondly, if the C.P.A. lay within the domain boundary. It was decided that the comparison of a single distance (the closest point of approach) to a safety threshold (the domange), as opposed to the comparison of an entire track with a hypothetical area around his vessel (the domain), was the procedure most likely to be adopted by mariners in practice. An initial hypothesis was assumed that: if the domain was infringed then it was infringed at the C.P.A.. Calvert (1983) showed that, for this to be true for all situations, any domain has to be a sector of a circle centred on own-ship. Thus in order to satisfy the hypothesis and to keep the model as uncomplicated as possible it was decided that the use of circular domains were required to determine whether or not a threat existed. The assumption was that there existed four "threat domains", which corresponded to the head-on, crossing, overtaking and stand-on encounters, each represented by a circle with own-ship at the centre. The prior discussion concerning the hypothesis that domains must be sectors of a circle might suggest the return to a Goodwin type of sectored domain. It would have been an unprofitable task to have defined the boundaries of each overlapping sector however, and so each encounter was assigned its own circular domain. The principle of assigning a different distance threat threshold to different encounters was used by Degré and Lefèvre (1983) in their automatic detection of encounters algorithm.

3.2.4.2 The determination of the domain radii

To determine the values of the radius of each domain a further analysis of the radar film was necessary. It was decided that the 24 mile film did not provide the required level of accuracy and so the twelve mile off-centred film was used for the analysis. All two-ship encounters were recorded; where an encounter was defined as two vessels having a P.C.P.A. of less than one mile. The value of one mile was chosen after an initial run confirmed that no vessels considered a P.C.P.A. of one mile to be threatening. The following variables were recorded:

a) the type of encounter (crossing, head-on etc.);

b) whether or not a manoeuvre was executed;

c) if a manoeuvre was executed, the initial predicted point of closest approach (P.C.P.A.);

d) if a manoeuvre was not executed the actual C.P.A.;

e) own-ship speed and type;

f) targets speed and type.

In the case of a head-on encounter first one ship and then the other was regarded as the give-way vessel, resulting in a head-on encounter registering two values. The variables measured in "e" and "f" will be further discussed and analysed in the section dealing with the simulation of an actual area of sea. The C.P.A. was considered positive if it resulted in the sight-line from own-ship to target rotating in an anti-clockwise direction (positive contribution) and negative if it resulted in a clockwise rotation of the sight-line (negative contribution).

For each type of encounter the proportion of vessels not manoeuvring when threatened by a target's P.C.P.A. (contribution initially ignored) was calculated. An estimate of the value of the domain radius for a particular encounter type was determined as being the P.C.P.A. at which half of the mariners were observed to take collision avoidance action. Prior to the analysis of each set of encounters the film was run to determine the maximum value of P.C.P.A. at which an encounter was observed to occur, this then became the upper limit for the following detailed analysis. Thus for the crossing encounters a maximum P.C.P.A. of 10 cables was chosen, whilst in the head-on and overtaking cases a maximum value of 8 cables was determined. Although the use of the 12 mile film meant that the majority of the simulation area to the north-east of the CS4 buoy was not covered, it was decided that mariners' actions were unlikely to vary a great deal over the length of the main lane, and consequently the use of any results obtained from the analysis were considered valid for the whole simulation area. It would clearly have been preferable to have been able to make use of the 24 mile film for this particular analysis, this was not however possible because of the lack of detail resulting in poor estimates of the P.C.P.A. and in some cases not being able to determine whether a manoeuvre had taken place or not. Some of the difficulties experienced in the use of the 12 mile film were:

a) the detection of overtaking manoeuvres because a large proportion of such encounters had already been resolved by the time the vessels had appeared on the radar film;

b) the initial determination of the P.C.P.A. in head-on encounters when the ferry from the continent bound for the U.K. altered course close to the separation boundary. This was because in many cases the coverage of the radar film resulted in an approximation with only two or three positions of the track of the ferry.

Further difficulties experienced in the analysis which were independent of the radar range scale used in the film were:

a) in distinguishing between main lane vessels moving into a formation by which to navigate the Strait and genuine overtaking encounters;

b) in the choice of which P.C.P.A. to assign to each vessel in the head-on encounter. It has already been mentioned that because both vessels can be give-way that two results are obtained from the one encounter. Clearly in most cases one vessel (A) alters before the other (B). It is obvious that the P.C.P.A. assigned to A is that of the initial encounter geometry, that assigned to B however is not so straight forward. It was decided that if B altered course less than two minutes after A had taken action then B's decision was too soon to have been influenced by the action of A and as a result it was acting to the threat of the initial P.C.P.A.. If however B either chose not to alter course or delayed alteration more than 2 minutes after A then clearly it was acting on information from A's initiative and as a consequence was considering the threat from the new P.C.P.A..

The results for each type of encounter are illustrated in Table 3.1. It can be seen that from a total of 497 observations 58% were crossing, 20% were head-on and only 22% overtaking encounters. Given the smaller numbers of observations for the latter two cases domain radii of 4.4 cables, 2.1 cables and 3.0 cables were obtained for the crossing, head-on and overtaking analyses respectively.

3.2.4.3 The effect of contribution on domain size

It was apparent from the radar film and from discussions with mariners that there was a significant variation in the threatening nature of an encounter in which the give-way vessel passes ahead of the target (negative contribution) and one in which it passes astern (positive contribution). It was decided therefore to consider the effect of contribution on each of the above analyses. In all cases a contribution of zero was taken to be positive.

Crossing encounter variation Table 3.2 shows the crossing analysis sub-divided in terms of the contribution. It can be seen that the domain sizes of 3.2 and 5.6 cables for the positive and negative contribution encounters respectively is far too great a difference not to be included in the computer simulation. In the radar film it was noted that ferries bound for the continent often altered course to come astern of through vessels. The result of this was that the through vessel often accepted a smaller negative P.C.P.A. than would have been the case without the ferries action. It was decided that there were not enough occurrences to make any significant statistical judgements on this action and so it was decided to use the values of 3.2 and 5.6 cables for the relevant domains.

An added advantage of the larger size of the negative contribution domain was that a vessel threatened by a target for which it is passing ahead would, in the simulation, alter course earlier than in a positive contribution encounter. The reason for this was that the R.D.R.R. determined the time before domain infringement, which was clearly earlier with a larger domain.

<u>Head-on encounter variation</u> It can be seen (Table 3.3) that for both the negative and the positive contribution analyses, the domain sizes are very similar, 2.0 and 1.75 cables for the positive (red-to-red) and negative (green-to-green) contribution cases respectively. It is interesting to note however that in the green-to-green, which is the more dangerous of the two meeting situations, the spread of P.C.P.A.s was greater. The reasoning behind this was probably that in the red-to-red situation a mariner would have no hesitation in manoeuvring at any P.C.P.A., whereas in the green-to-green encounter he always has the possibility of cancelling out any subsequent action by the target. Thus although he might feel just as threatened by a vessel passing on his starboard bow, he might feel inclined to take no action. It was decided that given the similarity in the domains sizes, it was preferable to be on the safe side and as a result a single domain of 2.0 cables was used in the simulation.

<u>Overtaking encounter variation</u> Domain sizes of 2.7 cables and 3.3 cables (Table 3.4) for the positive and negative contribution cases respectively suggest that a mariner regards overtaking with the target on the starboard bow (negative contribution) as being more dangerous than overtaking a vessel on the port bow, which was clearly to be expected. It was decided however that 42 observations for the positive contribution situation was not enough to give any significance to the estimate for the domain radius and so the overall result for the overtaking encounters of 3.0 cables was used instead.

Of more importance however were the number of negative as opposed to positive contribution encounters. 64% of the encounters for overtaking encounters were with the overtaken vessel on the starboard side. It can be seen then that although mariners regarded passing a vessel to port as more hazardous than to starboard the opposite was observed to occur. It was thought that a reason for this might be that although a mariner would prefer to leave adaquate room for manoeuvring to starboard, when in the Dover Strait, such an alteration would take his vessel into the English Inshore Zone (E.I.T.Z.). It was also clear, from the radar film, that the slower vessels tended to keep close to the northern boundary of the main-lane, presumably because for most destinations for through traffic it was the shortest route. This resulted then in the overtaking vessels more often being in the situation where an overtaking course to starboard would take them into the E.I.T.Z..

To summarize then the domain sizes to be used throughout the simulation were:

Crossing with positive contribution	-	3.2 cables;
Crossing with negative contribution	-	5.6 cables;
Head-on	-	2.0 cables;
Overtaking	-	3.0 cables .

3.3 R.D.R.R. Theory

In his computer simulation of shipping Davis (1980) used the off-centred domain to determine if a vessel was threatening and the arena to determine the distance from target, at which a manoeuvre was to be executed. The domain was apparently justified both from a questionnaire and from previous work carried out by Goodwin. The same cannot be said of the arena. The arena was simply a larger version of the domain (Fig.3.3), its dimensions adjusted in such a manner as to simulate correctly mariners behaviour. It was decided that the fundamental concept of when a mariner altered course for a threatening vessel needed careful consideration. The use of a model that was "tuned" to give the correct results was not sufficient. It was clear that a greater understanding of the mariners′ responses was required: the need for a complete reassessment of the situation was necessary.

One problem with the arena was its inability automatically to take into account different velocities, both of own-ship and of target. Nor could it make allowances for continuously varying relative velocities. Finally it was unable to compensate for any loss of speed through a manoeuvre. Holmes (1981) has shown the importance of speed, both relative and absolute, in the modelling of the time at which a mariner executed a manoeuvre. He constructed a mathematical model, which used the independent variables of own-ship speed and target speed to predict the indirect distance (the distance from own-ship to target via the intersection of the courses) at which a manoeuvre was executed. An initial solution appeared to be in the use of a speed

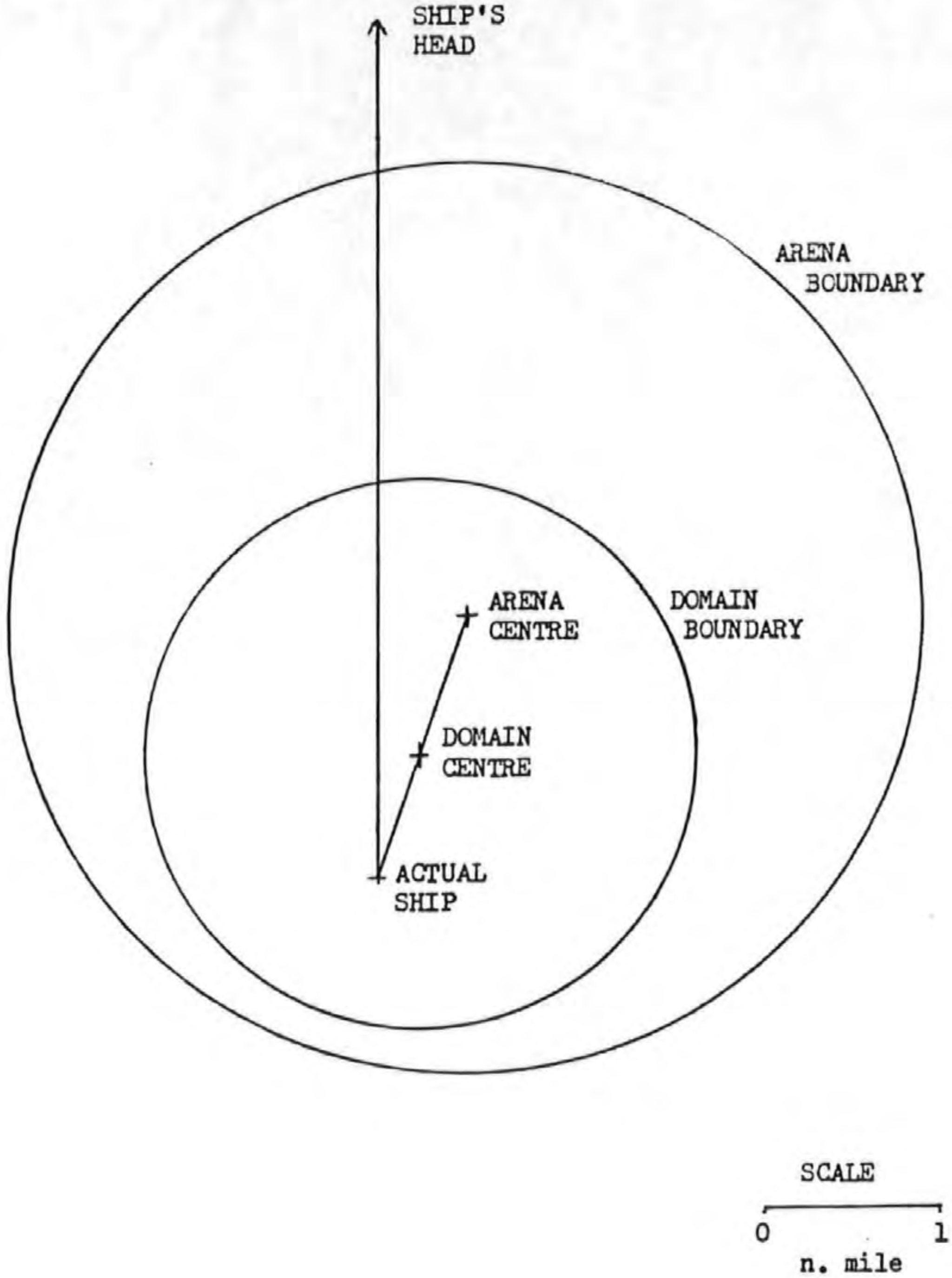


Fig.3.3 The Davis arena

dependent scaling factor. It was decided, however, that this would add increasing complication to an already unsubstantiated concept.

There existed four obvious means of determining the time at which to alter course. The first was as soon as it becomes possible to do so. This was quantified as being at whatever time, after initial detection of the target was needed to plot successfully and ascertain the dynamics and geometry of the situation. Calvert (1977) reasoned that early manoeuvres were inefficient in a routing scheme situation. If a vessel manoeuvred too early for a target then there was a reasonable possibility that the target would be required to make some other course alteration before the encounter was resolved, which, if the give-way vessel had delayed alteration, might have been eliminated. It was also shown that an early manoeuvre increased the chance of the vessel being involved in a multi-ship encounter (more than two ships involved in an encounter simultaneously). It was far more likely that for every encounter there existed an optimum time, at which to alter course, which was a function of the geometry and dynamics of the situation.

The second method was the use of a distance criterion. This corresponded to the concept of the arena used by Davis, for which the disadvantages have already been discussed. The use of a "time to go" criterion was utilized by Barratt (1980) for the detection of encounters for a radar film analysis by the then Department of Trade and Industry, National Maritime Institute (now N.M.I. Ltd., but to be referred to as N.M.I. in the following text). The "time to go" was calculated from the ratio of the range to the relative velocity. In this case if the "time to go" (T.C.P.A.) was less than 10 minutes then a possible encounter situation was recognized. Also, to detect close approaches at low closure rates, a minimum range of 1 n.mile was set. The use of a time criterion was also used by Degré and Lefèvre (1983) in their shore based collision avoidance system. The time chosen in this case was 15 minutes. The time criterion was discarded by Degré and Lefèvre, however, for a test based on the value of the course alteration ~~required~~ of the give-way vessel ~~for a vessel to alter course~~ to clear the target. Although this represented clearly the ideal manner in which collision avoidance should be initiated, it was decided that the average mariner would not have the the capability of using this procedure at sea. As a consequence it was judged that, although of obvious advantage in a warning system, its use was not justified in a model attempting to simulate realistically mariners' actions.

It was decided that the range to range-rate ratio, so successfully utilized in air traffic control, (Ratcliffe, 1982) would provide the foundation necessary for building a suitable model. Thus the vessel could be said to manoeuvre at some pre-determined time before C.P.A.. The idea was developed by Colley et al (1983) refer to paper included to be the time before the target would infringe the domain boundary (the Range to Domain over Range-Rate ratio - R.D.R.R.). It was found to be necessary to determine the time to domain boundary infringement as opposed to the time to C.P.A., because in situations where the vessels were closing on almost parallel courses the distance reduced to a negligible quantity, which was clearly unreasonable. With the R.D.R.R. the smallest distance at which the vessel altered course was at the domain boundary. The R.D.R.R. had the following advantages over the arena developed by Davis:

a) since the concept used the range-rate or relative velocity in its calculation, it had the ability automatically to take different ship speeds into account, so that two very fast vessels manoeuvred at a greater distance than two slower vessels;

b) the concept was able to distinguish between vessels approaching from different bearings, since this affected the relative velocity. Two vessels meeting head-on had a greater closing speed than two vessels involved in an overtaking encounter and as a result manoeuvred at a greater distance;

c) the model had the ability to take into account any reduction in speed by either the target or itself;

d) a stochastic variation in human reaction times could now be introduced as a statistical variation of the time criterion.

An analysis of the 12 mile radar film data was re-examined to verify the choice of the R.D.R.R. as opposed to the distance based criterion. Figure 3.4 shows the relationship between the time before C.P.A. and the distance at which manoeuvres were initated, for all the encounter types. The "L" shaped cluster of points suggested that there were two distinct groups of mariners: those who adopted a distance based and those that adopted a time based criterion. It was significant however that when the overtaking encounters were excluded the time based group became more dominant (Fig.3.5). The times were then adjusted to be the time to domain infringement or the R.D.R.R.

and Figure 3.6 shows the relationship between the two criteria. It can be seen that when the two points corresponding to very early manoeuvres in the overtaking encounters, which were not so much collision avoidance manoeuvres as manoeuvres to come into a formation by which to navigate the Strait, were excluded the sample was significantly dominated by the R.D.R.R. criterion. Although the initial scatter plot of the time to C.P.A. against the distance of manoeuvre suggested that the possibility of a time criterion with a limiting distance threshold might have proven to be realistic, it was decided that the incorporation of the distance (domain) into the model was a more mathematically elegant method.

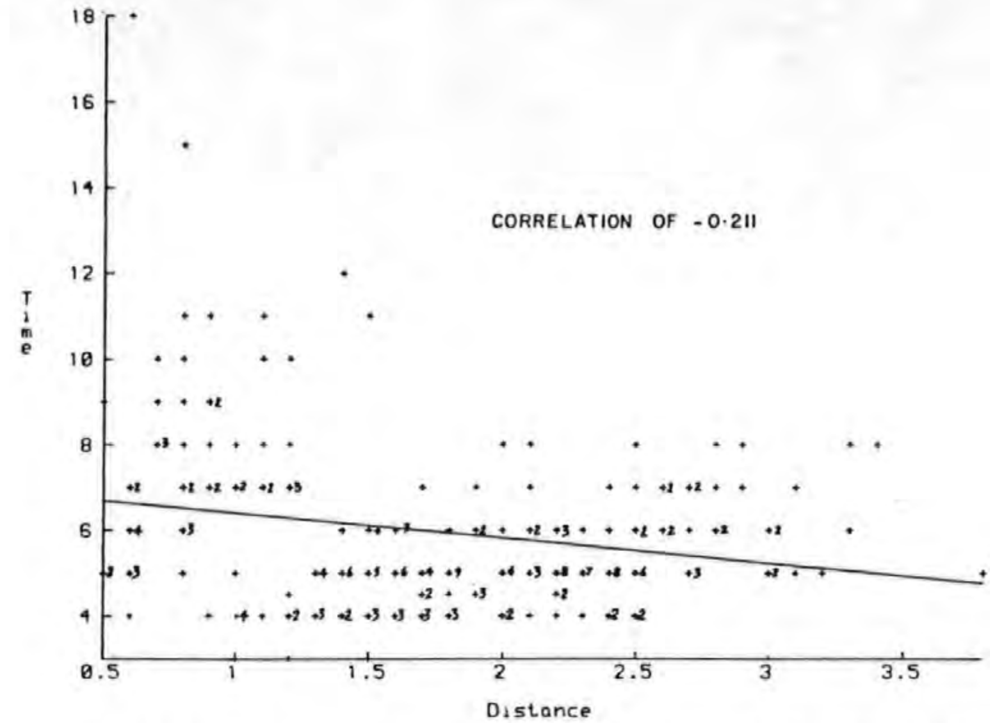


Fig.3.4 The relationship between the time before C.P.A. and the distance apart at the point of manoeuvre

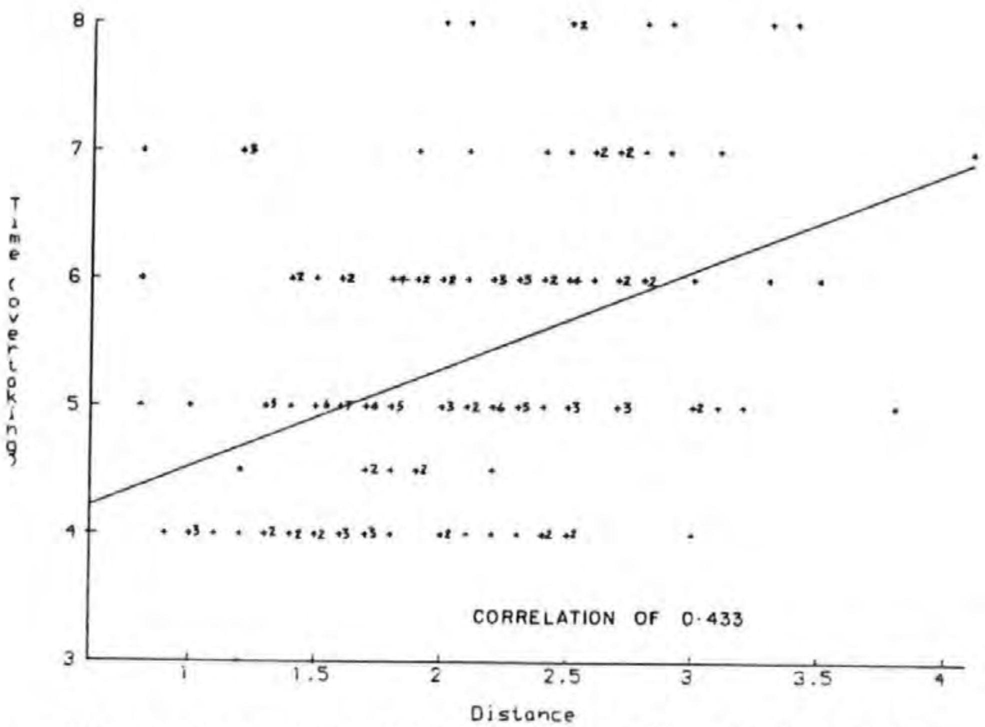


Fig.3.5 The relationship between the time before C.P.A. and the distance apart excluding overtaking manoeuvres

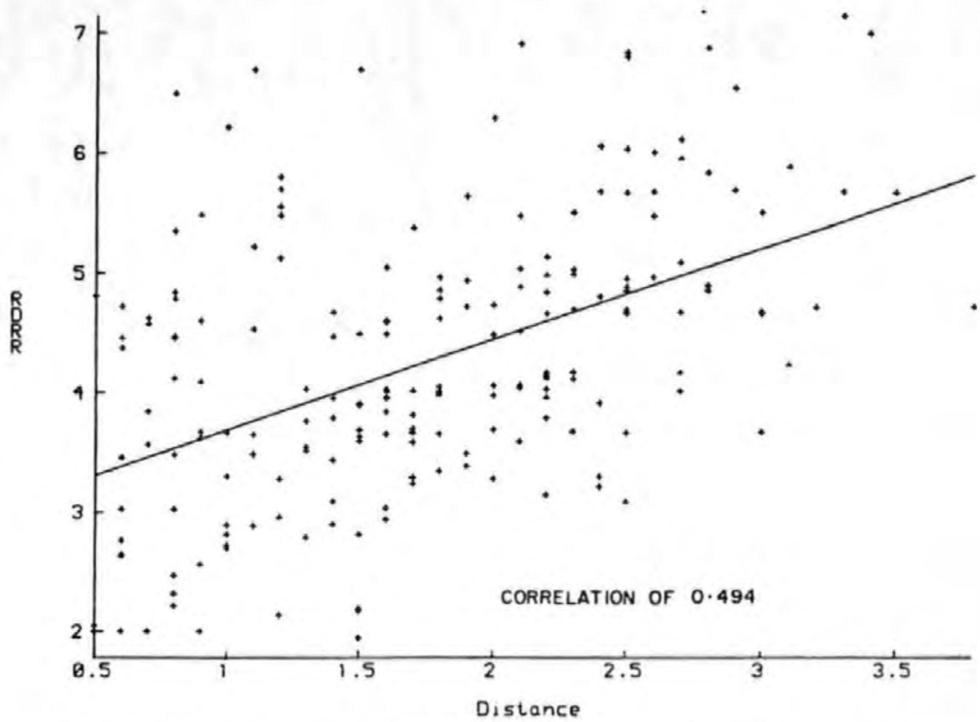


Fig.3.6 The relationship between the R.D.R.R and the distance apart for all manoeuvres

Table 3.1

Crossing encounters

Row 1	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Total
Row 2	7	39	49	28	19	17	3	0	1	0	163
Row 3	0	6	13	15	20	23	18	15	6	10	126
Row 4	7	45	62	43	39	40	21	15	7	10	289
Row 5	0.0	13.3	21.0	34.9	51.3	57.5	85.7	100.0	85.7	100.0	

Head-on encounters

Row 1	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Total
Row 2	4	8	9	2	3	0	1	0	-	-	27
Row 3	1	5	12	14	6	15	8	12	-	-	73
Row 4	5	13	21	16	9	15	9	12	-	-	100
Row 5	20.0	38.5	57.1	87.5	66.6	100.0	88.9	100.0	-	-	-

Overtaking encounters

Row 1	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Total
Row 2	8	14	11	8	2	0	1	0	-	-	44
Row 3	1	5	7	13	14	6	8	10	-	-	64
Row 4	9	19	18	21	16	6	9	10	-	-	108
Row 5	11.1	26.3	38.9	61.9	87.5	100.0	88.9	100.0	-	-	-

where:

Row 1 - P.C.P.A. range (cables);

Row 2 - Number of vessels manoeuvring;

Row 3 - Number of vessels not manoeuvring;

Row 4 - Total number of vessels observed;

Row 5 - Percentage not manoeuvring.

Table 3.2

Crossing encounters (contribution ignored)

Row 1	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Total
Row 2	7	39	49	28	19	17	3	0	1	0	163
Row 3	0	6	13	15	20	23	18	15	6	10	126
Row 4	7	45	62	43	39	40	21	15	7	10	289
Row 5	0.0	13.3	21.0	34.9	51.3	57.5	85.7	100.0	85.7	100.0	

Crossing encounters (positive contribution)

Row 1	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Total
Row 2	3	15	22	7	5	8	0	0	1	0	61
Row 3	0	5	11	9	9	15	8	5	4	3	69
Row 4	3	20	33	16	14	23	8	5	5	3	130
Row 5	0.0	25.0	33.3	56.2	64.3	65.2	100.0	100.0	80.0	100.0	

Crossing encounters (negative contribution)

Row 1	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Total
Row 2	4	24	27	21	14	9	3	0	0	0	102
Row 3	0	1	2	6	11	8	10	10	2	7	57
Row 4	4	25	29	27	25	17	13	10	2	7	159
Row 5	0.0	4.0	6.9	22.2	44.0	47.1	76.9	100.0	100.0	100.0	

where:

Row 1 - P.C.P.A. range (cables);

Row 2 - Number of vessels manoeuvring;

Row 3 - Number of vessels not manoeuvring;

Row 4 - Total number of vessels observed;

Row 5 - Percentage not manoeuvring.

Table 3.3

Head-on encounters (contribution ignored)

Row 1	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Total
Row 2	4	8	9	2	3	0	1	0	-	-	27
Row 3	1	5	12	14	6	15	8	12	-	-	73
Row 4	5	13	21	16	9	15	9	12	-	-	100
Row 5	20.0	38.5	57.1	87.5	66.6	100.0	88.9	100.0	-	-	-

Head-on encounters (positive contribution)

Row 1	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Total
Row 2	2	5	6	1	3	0	1	0	-	-	18
Row 3	1	3	10	7	4	5	3	6	-	-	39
Row 4	3	8	16	8	7	5	4	6	-	-	57
Row 5	33.3	37.5	62.5	87.5	57.1	100.0	75.0	100.0	-	-	-

Head-on encounters (negative contribution)

Row 1	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Total
Row 2	2	3	1	1	0	0	0	0	-	-	7
Row 3	0	2	4	7	2	10	5	6	-	-	36
Row 4	2	5	5	8	2	10	5	6	-	-	43
Row 5	0.0	40.0	80.0	87.5	100.0	100.0	100.0	100.0	-	-	-

where:

Row 1 - P.C.P.A. range (cables);

Row 2 - Number of vessels manoeuvring;

Row 3 - Number of vessels not manoeuvring;

Row 4 - Total number of vessels observed;

Row 5 - Percentage not manoeuvring.

Table 3.4

Overtaking encounters (contribution ignored)

Row 1	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Total
Row 2	8	14	11	8	2	0	1	0	-	-	44
Row 3	1	5	7	13	14	6	8	10	-	-	64
Row 4	9	19	18	21	16	6	9	10	-	-	108
Row 5	11.1	26.3	38.9	61.9	87.5	100.0	88.9	100.0	-	-	-

Overtaking encounters (positive contribution)

Row 1	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Total
Row 2	4	5	4	1	1	0	1	0	-	-	16
Row 3	1	2	3	5	5	0	3	4	-	-	23
Row 4	5	7	7	6	6	0	4	4	-	-	39
Row 5	20.0	28.6	42.9	83.3	83.3	-	75.0	100.0	-	-	-

Overtaking encounters (negative contribution)

Row 1	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Total
Row 2	4	9	7	7	1	0	0	0	-	-	28
Row 3	0	3	4	8	9	6	5	6	-	-	41
Row 4	4	12	11	15	10	6	5	6	-	-	69
Row 5	0.0	25.0	36.4	53.3	90.0	100.0	100.0	100.0	-	-	-

where:

Row 1 - P.C.P.A. range (cables);

Row 2 - Number of vessels manoeuvring;

Row 3 - Number of vessels not manoeuvring;

Row 4 - Total number of vessels observed;

Row 5 - Percentage not manoeuvring.

Chapter 4 The Ship Encounter Model

4.1 Mathematical Modelling

It is unlikely that the average mariner understands fully the debt owed by his profession to mathematics. The historical link was first forged by the astronomers (arguably the first branch of mathematicians) who presented the mariner with an accurate method of navigating his vessel. The contribution continued through spherical geometry, geodesy and cartography to the modern day electronic and computer orientated industry. In 1960 Calvert reconsidered the basic principles of collision avoidance, that had been established and consolidated over the years and had evolved into the Collision Regulations as they are known today. His research was based on contriving a mathematical model of the general encounter situation, from which manoeuvres that maximized the ability to increase the initial track separation could be formalized. He proved to be the instigator of a surge of interest in mathematical modelling applied to the encounter situation, which was followed by influential contributions from such people as Hollingdale (1961), Garcia Frias (1970), Thompson (1970) and Jones (1971). Hollingdale (1977) summed up the construction, use and importance of mathematical modelling to the mariner as follows:

> "...mathematics is being applied to the marine traffic problem at many different points. The most important single technique used in such applications is known as mathematical modelling. One constructs a mathematical model of the traffic situation, and then studies the properties of the model in order to obtain some insight into the behaviour of the "real" situation being modelled. A mathematical model

> consists, not of bits of hardware, but of sets of equations, inequalities and logical connectives. We evaluate its performance by solving the equations, etc., either by using the traditional techniques of the mathematician or, nowadays most likely, with the help of a computer to take care of the numerical chores."

It can be seen that Hollingdale, above, also introduced the process known as "computer simulation", to this branch of marine science.

The main aim then of this research was to formalize the rules and procedures adopted by mariners in the marine navigation- encounter-manoeuvre system. From these procedures and parameters representing the reactions of the mariners, a model was formed. There was no reason in principle why such calculations should not be carried out by hand. The advantage in the use of the computer lay in the speed of calculation of the computer and the ability to obtain a large volume of output in a short space of time. Once the validity of the model as a representation of the situation was established then experiments could be performed on the model virtually as they would have been in the real system had they been practicable.

4.2 Computer Facilities

The computer simulation model is a computer program, written in Fortran 77. The language was chosen for its ability to handle complex logical structures and mathematical expressions and of more importance its international standardization. This meant that, although the simulation was run on a PRIME 9950 computer, it is compatible with any system running Fortran 77. For this reason, although the PRIME implementation allowed some non-standard Fortran features, the standard was adhered to at all times. Careful consideration towards the compatibility of the program was also exercised in the choice of the graphical and mathematical libraries used within the program. All graphics were implemented by the universally available Gino-F and GinoGraf subroutines library, whilst the NAG (mark 9) routines covered any analytical or statistical algorithms.

4.3 Simulation Methodology

The model made use of a "continuous time" as opposed to a "discrete time" simulation procedure. Continuous time simulation implied that the physical situation was updated in its entirety every iteration (pre-determined interval in time). This method was suitable in any dynamic model where events were unpredictable or inter-dependant. An important decision, when using continuous time simulation was the value of the iteration time period. This was chosen as 20 seconds, to represent the shortest practical time period likely to be discerned in analysing mariners′ manoeuvring actions.

Discrete time modelling has most potential when events are discrete and instantaneous. In this particular situation it was found that events (encounters) often overlapped in time. Therefore more than just the one time flag would have been required to record the next event. It was found further to be impractical to derive an algorithm by which the magnitude of the manoeuvre could be pre-determined since it depends on the physical geometry of the situation in which other vessels might be considering change simultanously. Even if events had proven to be discrete, "discrete time" simulation would only have been justified if the system was dynamically stable (all velocities constant) for long enough to make an appreciable time saving.

4.4 Model Operation

The first stage of the present work was to simulate realistically individual encounters between vessels in the Dover Strait. From this it was hoped to increase the number of vessels simulated to cover at least one whole day's run through the main south-westbound lane. This development meant that a method of navigating ships on predetermined routes whilst avoiding sandbanks and shallow water had also to be included. The subsequent simulation of the Dover Strait system was consequently built around the initial model. In the following section the operation of the simple model is described and reference made to subroutines in the program. It was decided that for brevity the computer program which would have run into over 150 pages, would not be included in this thesis. It is however available on request to Dr. C.T. Stockel at Plymouth Polytechnic.

4.5 The manoeuvre-encounter system algorithm

The algorithms and logic used in all stages of the encounter, from the initial detection of the target to the final altering back on to course are described below. The structure and flow of the program was not described in detail as the emphasis had been on the operation as a whole. Figure 4.1 ~~clearly~~ shows the relationship between all the sub-programs used in the construction of the computer simulation.

4.5.1 Detection and recognition

As mentioned above the first stage in the encounter-manoeuvre system was the detection of a target and the subsequent classification of the encounter configuration. Each ship pair was considered in turn and the distance between the pair was calculated. No action was considered until the two vessels came within 6 n.miles of each other. At this point a delay of 3 minutes was introduced before the statii of the two vessels relative to each other was calculated. When this point had been reached, both mariners were said to have detected the other vessel on the P.P.I. and to have plotted a 3 minute vector triangle. The basic rules of good seamanship stipulate that once the status of a target had been resolved, the vessel would not be permitted to alter its decision. Hence the relative status for the ship pair was determined and fixed for the duration of the encounter.

The statii of the two vessels, relative to each other, were determined by the relative sector in which the other vessel lay and the speeds of the two vessels. No combinations of encounter type that were not permitted in the Collision Regulations were allowed in the simulation. Thus the combination of one vessel being assigned the status of overtaking, while the other was assigned the status of crossing could not be generated by the computer program. The following were the permitted combinations for the encounter statii:

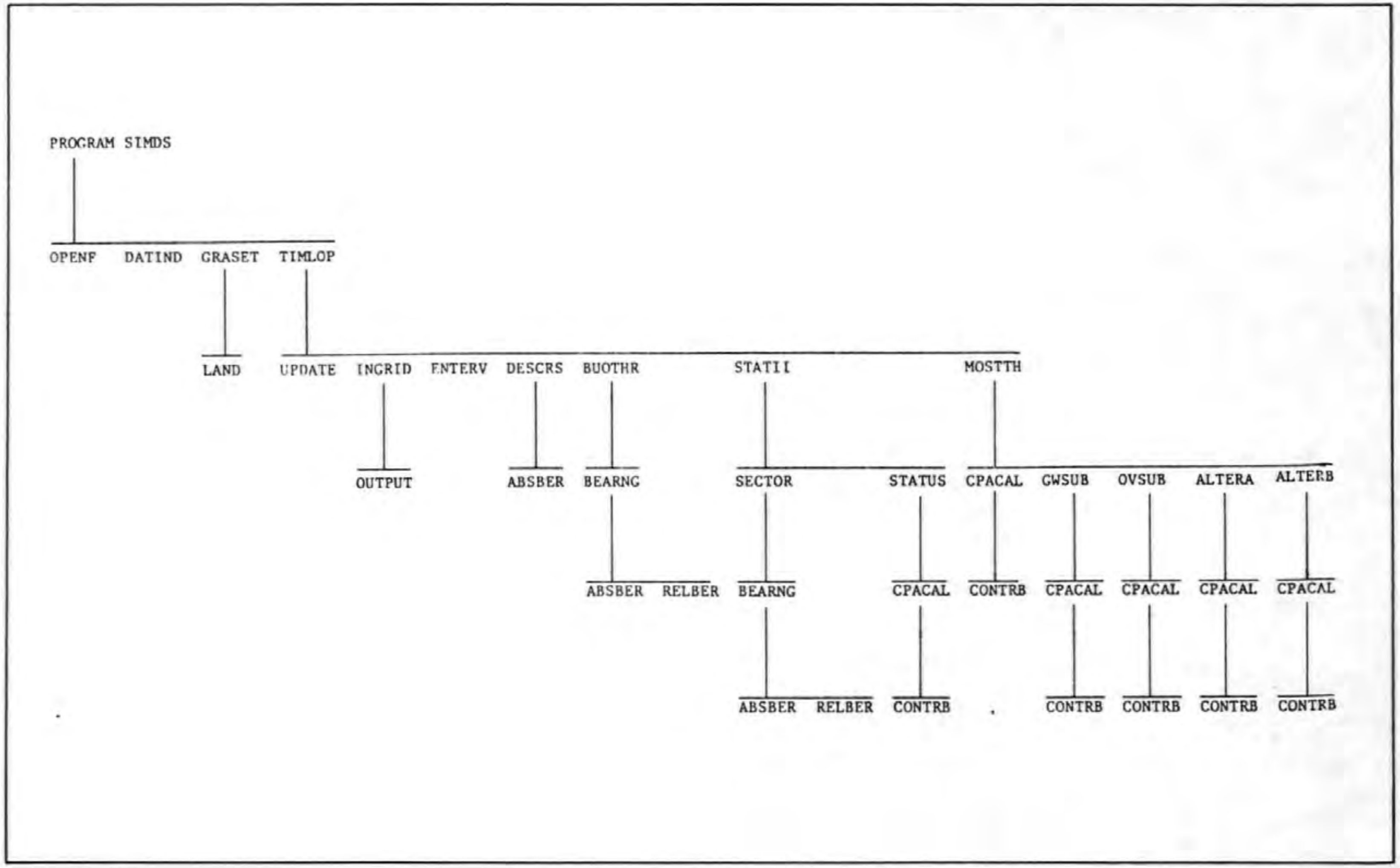


Figure 4.1 The structure of sub-programs within main program SIMDS. Program progression is from left to right and from top to bottom.

head-on,	stand-on;
head-on,	head-on;
crossing,	stand-on;
overtaking,	stand-on.

It can be seen that the only combination that allowed neither of the vessels to be stand-on was the head-on encounter. In this situation both vessels were assigned the status of head-on, but if one of the vessels altered course before the other felt it was necessary to do so, then it could result in one of the vessels not being required to make a collision avoidance manoeuvre (C.A.M.). The sector in which the own-ship defined the target as lying was solely a function of the relative bearing. The sectors were defined as follows:

$355.0 < \theta < 112.5$ starboard sector (Sector 1);

$112.5 < \theta < 247.5$ stern sector (Sector 3);

$247.5 < \theta < 355.0$ port sector (Sector 2);

where θ is the relative bearing of the target ship.

Note that the starboard sector was extended by 5 degrees on the port bow, so as to give a realistic positive bias to the encounter being regarded as conventional (interpretted as requiring an alteration of course to starboard).

4.5.2 When to manoeuvre

As had been discussed above (Section 3.3) the vessels manoeuvred at a time, which was a function of the type of ship, before domain infringement. The time to domain infringement was calculated as being the ratio of the range minus the relevant domain radius to the range-rate (the range-rate was calculated easily as the vector addition of the two velocities).

4.5.3 Execution of manoeuvre

It was decided that although in practice a mariner would determine initially if a vessel was threatening and then if necessary, alter course, it was computationally more efficient to reverse the process in the computer simulation. Clearly since the threshold level at which the decision to manoeuvre is reached occurs only when both conditions are satisfied then the order in which the criteria are determined makes no difference to the final outcome. Hence when the time to take evasive action arrived the C.P.A. was determined and the existence of a threatening or non-threatening situation established. If the target was threatening then the own-ship considered the necessary course of action, otherwise the possibility of threat was reassessed every iteration (20 seconds).

The situation became more complicated when two or more targets were threatening own-ship simultaneously (multi-ship encounter). In all cases, when determining if the target was threatening, the T.C.P.A. in addition to the C.P.A. was calculated. The own-ship then used the T.C.P.A. to determine the most threatening target, which, in a multi-ship encounter, always was the target with the smallest T.C.P.A.. The use of the T.C.P.A. as the criterion for determining the most threatening ship could not be qualified from the analysis of the data as the sample of multi-ship encounters was not large enough. It was a reasonable assumption to make, however, that the time available was a suitable means of differentiating between simultaneous threats. The one other advantage in its use was that it supported the use of the R.D.R.R. model, which was in its most basic form the T.C.P.A.. It followed then that at the time that the target came within the predetermined time criterion, if the own-ship had not taken action for another target, then the target was also the most threatening vessel.

4.5.4 Head-on procedure

Once a target had been identified to be a threat and to be the most threatening ship, then the next stage was the evaluation of the subsequent action. The initial aim was the determination of the sign of the turn and the limiting course that a vessel must not alter past. These were found using different logical processes depending on the type of encounter.

The head-on encounter provided the greatest variability in manoeuvres of all the meeting situations. When both vessels had the other on the port bow (red to red) the decision concerning the nature of the collision avoidance action was that provided by the Collision Regulations: alter course to starboard, and as such was unambiguous. As Kemp (1973) concluded, however, a significant number of mariners were prepared to attempt to increase the initial miss distance in the green to green head-on situation (both vessels have the other on their starboard bow), by an alteration of course to port. As is discussed later this action was noticed to be prevalent between meeting ferries. The action of one vessel altering course to port can be hazardous, with a large number of collisions having been the result of one mariner attempting to increase his miss distance by altering course to port, while the other either stood-on or felt threatened and in following the Collision Regulations, altered course to starboard and cancelled out the contribution which had been acquired from the initial alteration. The collision between the Brazilian "Horta Barbosa" and the South Korean "Sea Star", in the Gulf of Oman, December 19th., 1972 (Cahill, 1983) illustrated the situation in which one vessel altered to port whilst the other stood-on. A well known collision which had resulted from a cancellation of contribution, was between the "British Engineer" and the "Karanan", in 1945, in which the "British Engineer" altered course to port and the "Karanan" altered to starboard (Cockcroft and Lameijer, 1982). In the case of ferries meeting however the use of V.H.F. radio communication and a familiarization with their colleagues' actions meant that a misunderstanding and hence the cancellation of contribution should have seldomly occurred (the author has, however, observed several near misses between ferries following a port alteration).

It was decided that a manoeuvre to port was to be permitted in the computer simulation. The structure of the program did not allow both vessels to alter course in opposing directions and consequently the cancellation of contribution did not arise. Although it has been stated above that the model attempts to simulate the collision avoidance procedures specified by the Collision Regulations, it was felt that the frequency of the port alterations justified their inclusion.

It was decided that the criterion for a port alteration was to be: if the encounter possessed negative contribution and the initial closest point of approach was greater than half the domain. The only other head-on situation, at present, in which a vessel had designated a course alteration to port, was when the other vessel had already started altering course to port and a starboard alteration would have resulted in the two manoeuvres cancelling each other.

Once the decision had been made to turn to port or to starboard, an alteration of course was made. The new course was tested in subsequent iterations until the vessel no longer infringed the other vessel's domain. The vessel was not permitted to alter past a right angle from its initial course.

The vessel started to alter-back on to course as soon as the other vessel had fallen abaft the beam (relative bearing was greater than 90 degrees), and a return to course was no longer infringing the domain.

4.5.5 Crossing procedure

The crossing situation was much more straight forward than the head-on situation because a vessel was only permitted to alter course to starboard. The only complication, to the procedure followed through this encounter, was that a vessel did not stop altering away from the target as soon as its domain was no longer infringed, but continued until it had brought the target onto its port bow. The modification to the initial assumption of merely clearing the domain was a result of feed-back from the computer radar simulation experiment (Chapter 9). It was pointed out that in most crossing situations a vessel altered course at least until the target was on the port bow. The actual test used in the simulation was that the vessel alters course until the domain was cleared and the target's relative bearing was to port.

The decision to alter-back was not considered until the target had passed further astern than 15 degrees on the port bow. At this stage the domain was checked for infringement given the new course at the following iteration, and if clearing the vessel proceeds with the alteration. Domain infringement was reassessed prior to each subsequent alteration back onto course.

4.5.6 Overtaking procedure

The head-on encounter had a variability in mariners' actions because of the existence of the alteration to port. Overtaking vessels are also permitted, by the Collision Regulations, to alter course to port, but in more obvious and less ambiguous circumstances. The mariner had to consider the following points before deciding on his alteration:

a) an alteration of course to pass astern of the target would resolve the threatening situation far more rapidly than paralleling the target's course and then passing ahead and would have the added benefit of being obvious to any other vessels and in particular to the overtaken ship;

b) an alteration to overtake a vessel on the starboard side would leave the overtaking vessel with sea-room to starboard should a subsequent encounter require further give-way action to starboard;

c) the contribution of the encounter might mean that an alteration to pass astern would be totally inefficient, requiring the vessel to make a substantial alteration to even clear the target.

It was decided that the mariner's priorities were:

a) to always pass astern when the vessel was on the starboard bow. Thus satisfying the preference to leave room to starboard and to pass astern;

b) to parallel the target's course if the target was to port initially and own-ship was passing ahead (positive contribution) and a paralleling of the course would not infringe own-ship's domain given its present position relative to the target or otherwise to pass astern.

A different situation arose if the two vessels were initially on near parallel courses (a frequent situation with vessels passing down the routing scheme). In this situation the preference was always to alter course to starboard. The give-way vessel stopped altering away as soon as the domain was no longer infringed.

An alteration back onto course commenced as soon as the target was observed not to be threatening given a return to the initial or desired course by own-ship. In all the other encounters a vessel was not permitted to return on to its desired course until the target was no longer regarded as a threat. The use of the measure of time before domain infringement and the small relative velocities that can occur in overtaking encounters often resulted in vessels manoeuvring at 10 to 20 minutes before the C.P.A.. If in these circumstances the overtaking vessel had been restricted in altering back until the target was no longer a threat (abaft the beam) then it could well have manoeuvred an unreasonable lateral distance off the track. Given a typical course alteration of 20 degrees for a vessel travelling at 16 knots and held for 10 minutes, the vessel would have been forced off its track by 9 cables. Furthermore it was quite feasible that the relative velocity between the two vessels was so small that as soon as the overtaking vessel altered course, then its reduced forward velocity component would result in it no longer gaining on the target and hence never altering back on to course.

Chapter 5 The simulation of continuous traffic

5.1 Introduction

In the earlier development of the computer model many generalizations and simplifications were made about the mariners' actions and the characteristics of the ships involved. This was justified because the initial stages were not concerned with simulating the area as a system but rather encounters in isolation. In such an encounter the starting positions, courses and speeds of the ships involved were predetermined so as to ensure the need for collision avoidance. The main aim then was to verify the vessels' choices of statii and the logical flow of consequential manoeuvres. The magnitude and duration of the manoeuvre were of secondary importance. In the simulation of a traffic system, the snow-ball effect of one vessel's actions on the rest of the shipping system required that more research be directed towards a more precise modelling of the ships' dynamics and the stochastic element in the system.

5.2 Speed changes in the model

5.2.1 Acceleration and deceleration

No attempt was made initially to simulate the deceleration of a vessel through a turn and the subsequent acceleration once back onto a stabilized course. The result was that all manoeuvres that took place at a steady rate of turn were always arcs of circles. Since the natural deceleration through a turn also has the effect of reducing the turning circle, it was decided that the inability to model the speed changes resulted in a disadvantage to the simulated vessels. Lewison (1973) indicated that away from the origin, speed loss was approximately proportional to rudder angle. If the further assumption was made that the non-dimensionalized speed loss, was constant throughout the turn, then an approximate value could be obtained, from ships' trials, that allowed the speed loss to be determined, at each iteration, for a vessel altering course. The loss in speed was a function only of the speed before the turn commenced and the rate of turn. The value was obtained from the turning test for the "Saudi Abha". The simplification of the dynamics was felt to be justified in the circumstances, because the inclusion of a sophisticated model would have been costly in terms of computer time and space and the actual manoeuvring responses were of minor importance with respect to the decision making process. The use of only one vessel's characteristics was because of the lack of available data concerning speed loss through a turn.

5.2.2 Controlled reduction of speed

All vessels in the simulation were injected at their normal operating speed and this was also taken to be their maximum speed. In the simple encounter model there was no requirement for speed reduction. It was found necessary however in the simulation of a physical area of sea to incorporate the ability for a mariner to reduce speed. It has been mentioned in this section as part of the general process by which a vessel accelerated or decelerated in the model.

At each iteration the total acceleration due to course alteration (negative acceleration) and any specified change in speed as a collision avoidance process in its own right was found. This was then applied to the vessels speed to obtain the updated speed. The vessel was not allowed to accelerate past its operating speed nor to drop below 0.25 of its operating speed.

5.3 The variation in mariners' reactions

One of the most basic assumptions made in the construction of the computer simulation was that there existed an average mariner, whose actions were representative of the mariner population using the Dover Strait. Although the range of mariner characteristics and the situations in which a particular mariner might find himself were as diverse as in any other profession, it was decided to be a reasonable basis on which to build the model. When as many as 220 vessels, 12 different routes and 6 ship types were being simulated then the concept of using average actions and reactions needed careful reconsideration.

One of the disadvantages in the use of the radar film as a source of data was in the difficulty of extracting information relating to the types of ships involved. In the man-ship control system it was clear that both the mariner and the type of ship he was commanding added to the variability in observed actions. To make any conclusions, therefore about the nature of the mariner's actions necessitated information concerning the variation due solely to the type of vessel. It was because of the inadequacy of the radar film data in that respect that the use of information obtained from observations of the mariner at sea became important. This was made possible firstly, thanks to P & O Ferries, with a trip on-board a ferry from Dover to Boulogne and secondly a voyage, via a container vessel, from Southampton to Hamburg. In both these trips the researcher was allowed to observe all actions taking place on the bridge. It was concluded that there were three main areas in the encounter- manoeuvre system in which a variability in actions was observed: the threat level; the corresponding time at which action was taken if deemed necessary and the magnitude of the resulting manoeuvre.

The greatest variation was observed in the threat level: the level at which the mariner decided that a target was threatening. The main conclusion drawn from the observations was that the most significant factor in the determination of what constituted a threat, apart from the geometry of the situation, was the type of vessel the mariner was controlling. Of secondary importance was the target type and of least significance was the personality of the mariner himself. The obvious reason for the lack of variability in the actions of different mariners navigating the same vessel and in the same encounter situation was that guide lines were passed on by the more experienced mariners to those less familiar with that particular vessel. It was clear then that any variation in the determination of threat could not be applied arbitrarily to vessels in the model since this would have reflected a variation in mariner responses, but rather it would have been implemented as a function of the own-ship and target types. The data used in determining the domain boundaries for the whole shipping sample was quite adaquate in terms of the number of observations, its use however, when sub-divided into ship types would have reduced the statistical significance to an unacceptable level.

The time at which the alteration took place was modelled by the R.D.R.R., and was designed essentially to incorporate a degree of variation. This was visible in its ability to distinguish between ships of different speeds. Curtis (1978) considered the variation in mariners' reaction times using a carefully prepared overtaking exercise on the City of London Polytechnic's Radar simulator. He determined the time taken by the ship to take avoiding action to be in two parts:

a) the time taken by the overtaking ship to observe that the overtaken ship had altered course, plus the time required to consider the action to be taken;

b) the time required by the ship dynamics to manoeuvre clear.

From his experiments Curtis calculated a mean reaction time of 2.9 $\mp$ 0.2 minutes. Figure 5.1 shows a histogram of the observed reaction times for his subjects.

It became apparent that there was a need to distinguish between the results obtained by Curtis and the requirements of the computer simulation. The obvious distinction to be made was that Curtis's experiment was clearly defined as running in poor visibility

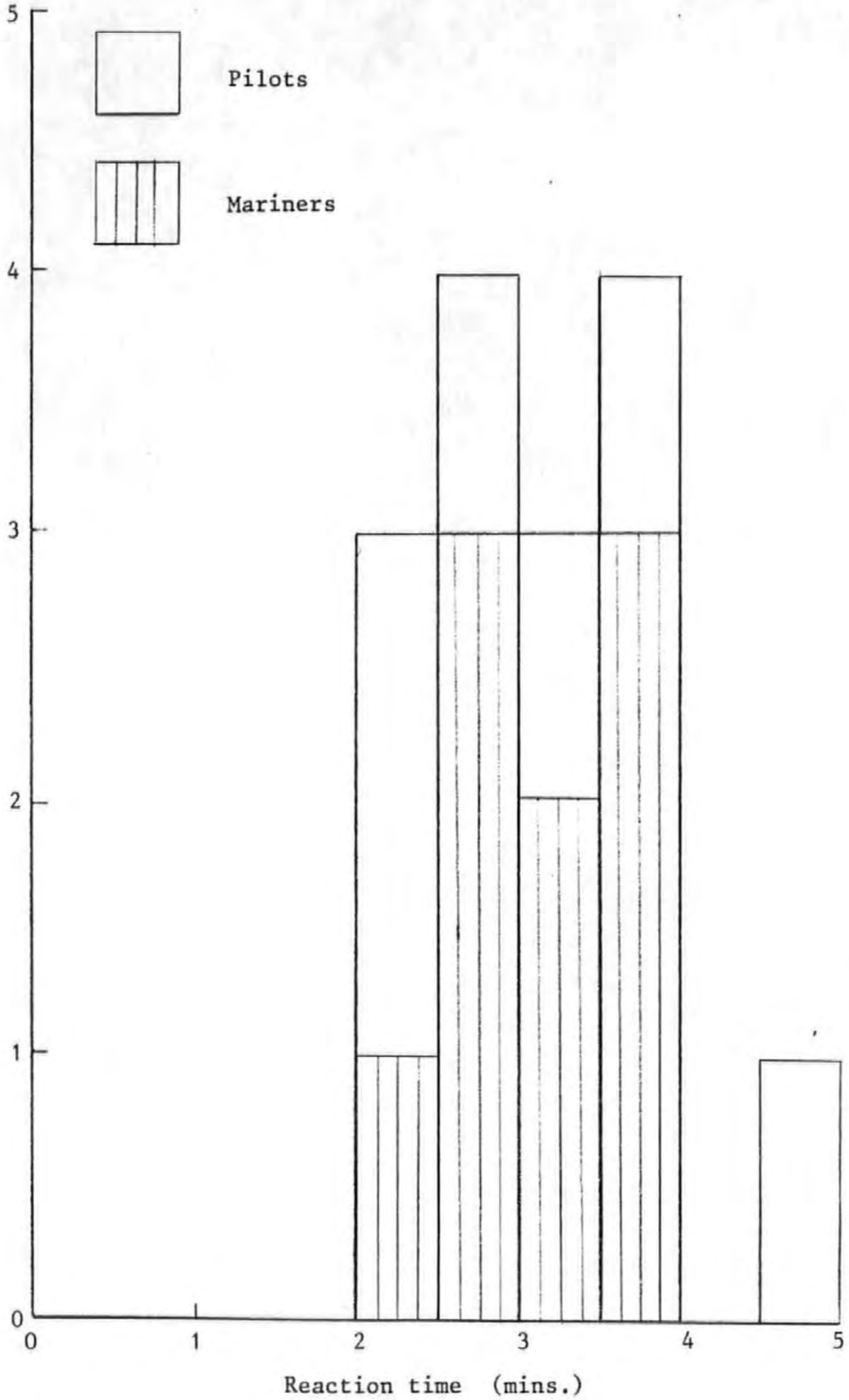


Fig. 5.1 Histogram of observed reaction times

conditions. Clearly the purpose of the research carried out by Curtis was to consider a mariner's reactions and as a consequence the exercise was designed to provide a sudden, unexpected stimulus, which as a step response in any reaction experiments, provided results that contained solely the reaction time. The mariner had no time to premeditate his decision, all that was required was action. The model, however attempted to simulate the controlled situation and was therefore much less dependant on the reaction time. It was likely that the reaction time was significant in the initial detection of the target, but since it had been shown that the point of manoeuvre occured some time after the initial detection then clearly by that stage the influence of the reaction time element was lost.

It was decided then that, since the use of a "time to go" concept was used and that as a consequence the different ships closing speeds were contained automatically in the R.D.R.R. that the use of the mean and standard deviation of manoeuvring times observed from the radar film would be a valid means of obtaining normally distributed times in the simulation. As a consequence a normally distributed random number with mean 5.0 minutes and standard deviation 1.7 minutes was generated with a cut off point of 1 S.D. on each side to reject extreme values.

The final area in which a variation in observed actions was observed was in the magnitude of the collision avoidance manoeuvre. It has been shown that the initial concept of just clearing the domain was modified to be a large enough alteration to bring the target onto the port bow. It was decided that the rule was known to be one of good seamanship and that although a variation had been observed in practice that no such deviation could be applied within the limitations of this rule. The model allowed some variation in the magnitude of the collision avoidance manoeuvre as a function of the physical constraints on a vessel in a particular situation. These included firstly the ability to stop altering for the original target and to continue the alteration for a new, more threatening target and secondly the possibility of terminating the manoeuvre away as soon as the domain was clear in conditions of high traffic density. It was decided that although too little data was available to make any valid conclusions from the observed situation that these variations reflected realistically those shown in practice at sea.

To conclude then the variability of mariners' reactions has been simulated in the model to some degree with the use of the R.D.R.R. concept. There was however a danger in incorporating a mariner's reaction time as observed by Curtis because it related to an emergency action situation as opposed to a controlled situation as required by the computer model. Lastly care was required in differentiating between the variation due to the differences in the ships involved and the inherent variation in mariners' characteristics.

Chapter 6 The Main South-Westbound Lane Simulation

6.1 The Dover Strait Traffic Separation Scheme

The Dover Strait which at its narrowest point is eighteen nautical miles wide, is an area of significant potential hazard (Fig.6.1). The traffic is divided into four zones (English inshore, main south-westbound lane, main north-eastbound lane and French inshore). In 1961 the Institutes of Navigation of Britain, France and Germany formed the first Working Group to establish a plan for separating traffic in the Dover Strait. The plan was voluntarily brought into force through the Inter-governmental Maritime Organisation (I.M.O.) in September 1967. The collision between the "Pacific Glory" and the "Allegro" in 1970 first drew attention to the dangers of the Channel. It was not, however, until the "Texaco Caribbean" - "Paracos" collision on 11th. January 1971, followed the next day by the "Brandenburg" hitting the wreck and culminating in the "Niki" striking the wreckage again on 27th February that pressure was applied to the Government to improve the situation (Hargreaves, 1978). The routing scheme came into full operation on 31st July 1972. It was supervised by H.M. Coastguard, which provided a 24 hour surveillance of the Strait over an area within 16 miles of the radar station at St. Margaret's Bay, Dover. It was not until July 1977, with the implementation of the 1972 IMCO revision of the Collision Regulations, in which the conduct of vessels using Traffic Separation Schemes was prescribed under Rule 10, that it became, for the first time, binding on ships of all nations signatory to the 1972 Convention to adhere to the established routing scheme (Johnson, 1978). Cockcroft (1983) produced a survey of the collisions in the Dover Strait over periods relating to the developments in the routing scheme and concluded that there has been a significant improvement at each stage in the development (Table 6.1).

Table 6.1

Collisions in the Dover Strait according to encounter situation

	1957-61	1962-66	1967-71	1972-76	1977-81
Opposite directions	45	47	27	7	3
Broad Crossing	0	0	0	0	2
Same direction	6	7	8	6	7
Not known	1	2	1	1	0
Totals	52	56	36	14	12

The Dover Strait was chosen for the following reasons:

a) the significant potential hazard inherent in the area necessitated a means of measuring the efficiency of the present system;

b) the high possibility of partial obstruction of the Traffic Separation Scheme (T.S.S.) such as pipe laying operations, Navy manoeuvres or future oil-drilling activities required a model that could consider the advantages and disadvantages of subsequent modifications;

c) the availability of high quality 16mm. radar films provided a good coverage of the area;

d) the close proximity of ferry masters and other professional seamen making constant use of the area, whose assistance provided useful hints and data.

6.2 The Main South-westbound lane

A further decision was taken, to produce the computer simulation of shipping through a limited section of the main south-westbound lane (the main lane), from the Varne light-vessel to the South Falls. It was felt that the simulation of the main north-eastbound and the main south-westbound lanes was unnecessary because of their mutual independence due to the separation zone. Thus the modelling of both lanes would have effectively resulted in two independent models being created, resulting in a duplication of effort. The 12 n.mile radar film was also limited to coverage of the English Inshore zone and the main South-Westbound lane and consequently the assumption that vessels in the main north-eastbound lane behaved like their neighbours would have been required.

6.3 Traffic flow through the Dover Strait

6.3.1 The problem

In the simple ship encounter model each vessel was set up with an initial course, speed and position. Since one was only interested in their relative positions to each other there was no need for any form of navigation, the desired course was always taken to be the initially designated course. Clearly when simulating an area of sea the provision for the vessels to make navigational course alterations must be incorporated. Since no two vessels follow exactly the same route and an individual route specification for every vessel entering the scheme was unreasonable, the most frequently used tracks were determined. In the following section different approaches to the problem of track generation are considered. It should be noted that all perform a smoothing or approximation in determining the routes to be used.

It might appear that a suitable method of generating the different ship's desired routes would have been to define each ship route as a set of new desired courses at set durations into the scheme. Indeed this approach is used as a means of setting the tracks of target ships in the majority of radar simulators. This method fails, however, when a vessel is forced to make a collision avoidance manoeuvre. There are two reasons for this: firstly, any collision avoidance manoeuvre will slow the vessel's progress and result in all subsequent navigation alterations occurring at a shorter distance into the scheme; secondly this method has only the capability of recording one particular desired course at any stage in the route, once a vessel has been forced off the route there is no way of compensating for the resulting lateral displacement.

6.3.2 The Degré and Lefèvre track generation method

Degré and Lefèvre (1978) categorised all ship tracks by their origin and destination. Using data from the French Transport Research Institute (I.R.T.) traffic was divided into a number of lanes, each relating to an origin-destination route, inside which the vessels had to navigate. The boundaries to these lanes or beams were defined by the nature of the route, the routing scheme and any natural obstructions such as sand-banks. Ship tracks were then generated inside these beams by determining navigational course alterations at selected lines along the beams. These lines were called course lines and they were each divided into six equal length sub-sections. Each of these sub-sections contained the probability of the vessel navigating through each of the sub-sections in the subsequent course line.

Degré and Lefèvre determined the distributions of ships along the course lines by counting the number of vessels passing through each sub-section (usually referred to as "gates"). From these sample distributions they then determined the probability that a vessel would pass through that particular gate. This method was not felt to be suitable for the present simulation for the following reasons:

a) one of the aims of the research was to study the effect of manoeuvres on the distribution of vessels at gates. The assumption that distributions are due entirely to navigation alterations is therefore misleading. The requirement is for a means of determining the ideal routes along which a mariner would navigate and to then analyse any subsequent differences in the distributions and to calculate the effects of alteration;

b) another objective was the introduction of an obstruction in the scheme. Under these conditions the highly detailed probabilities cannot be substantiated. The preferred course of action in this situation was to use the same predetermined routes and the addition to the rules governing the mariner's actions of an algorithm for avoiding a large obstruction;

c) the containing of vessels to lanes, however wide, is too restrictive to a model aiming to be capable of simulating all possible occurrences. There was no practicable method of dealing with vessels that through unavoidable collision avoidance manoeuvres found themselves outside the boundaries of the beam.

6.3.3 The O.R.P.A.T.S. orientation points method

Another approach used in navigating vessels through an area of sea was that used by Spaargaren and Tresfon (1978) in their Observation Related Port Approach Traffic Simulation (O.R.P.A.T.S.) model. Their model dealt with a port approaches simulation and the emphasis was consequently on the interactions of many ingoing and outgoing vessels, all of which were on well defined and inherently restrictive tracks. The method was the use of several orientation points (O.P.). A vessel navigated from one O.P. to the next; whenever a vessel was within 400 metres of an O.P. it changed course for the next scheduled O.P.. Thus each route was represented by a set of ordered O.P.s. The use of O.P.s for a port approaches simulation appeared to be an excellent idea, but its usage was limited in a more expansive system such as the Dover Strait. It also suffered from the drawback noted with the Degré and Lefèvre project in that it had difficulty in dealing with large lateral displacements resulting from collision avoidance manoeuvres. In this case a vessel would find itself having to make an alteration back onto course of the same sort of magnitude as the initial manoeuvre away. A further problem was identified in the implementation of Rule 10c. The only method of directing a vessel across the routing scheme at 90 degrees from any position along the boundary, with the restricted use of O.P.s alone, would be by positioning an O.P. at a great distance from and perpendicular to the boundary. Clearly the vessel would never then arrive at the O.P. and hence a difficulty would occur in determining when it was to alter course on its new track.

6.3.4 Route implementation in the simulation

6.3.4.1 The grid

It was decided that the most flexible means of describing the ship tracks through the Strait was to superimpose a grid over the area of interest. In order to maximize the area covered by the grid, the abscissa was rotated to run parallel to the northern boundary of the main south-westbound lane (the main lane). Figure 6.2 shows the orientation of the grid, with the origin approximately four miles south of the Varne light-vessel. It has dimensions of 20 miles by 10 miles and covers all of the main lane from the Varne up to the South Falls buoy and stretches far enough north-west to include the entrance of the Dover harbour.

The grid was sub-divided into one mile square elements. The tolerance of one mile was felt to be sufficiently accurate to simulate the ship tracks, without being too costly in terms of the required computer

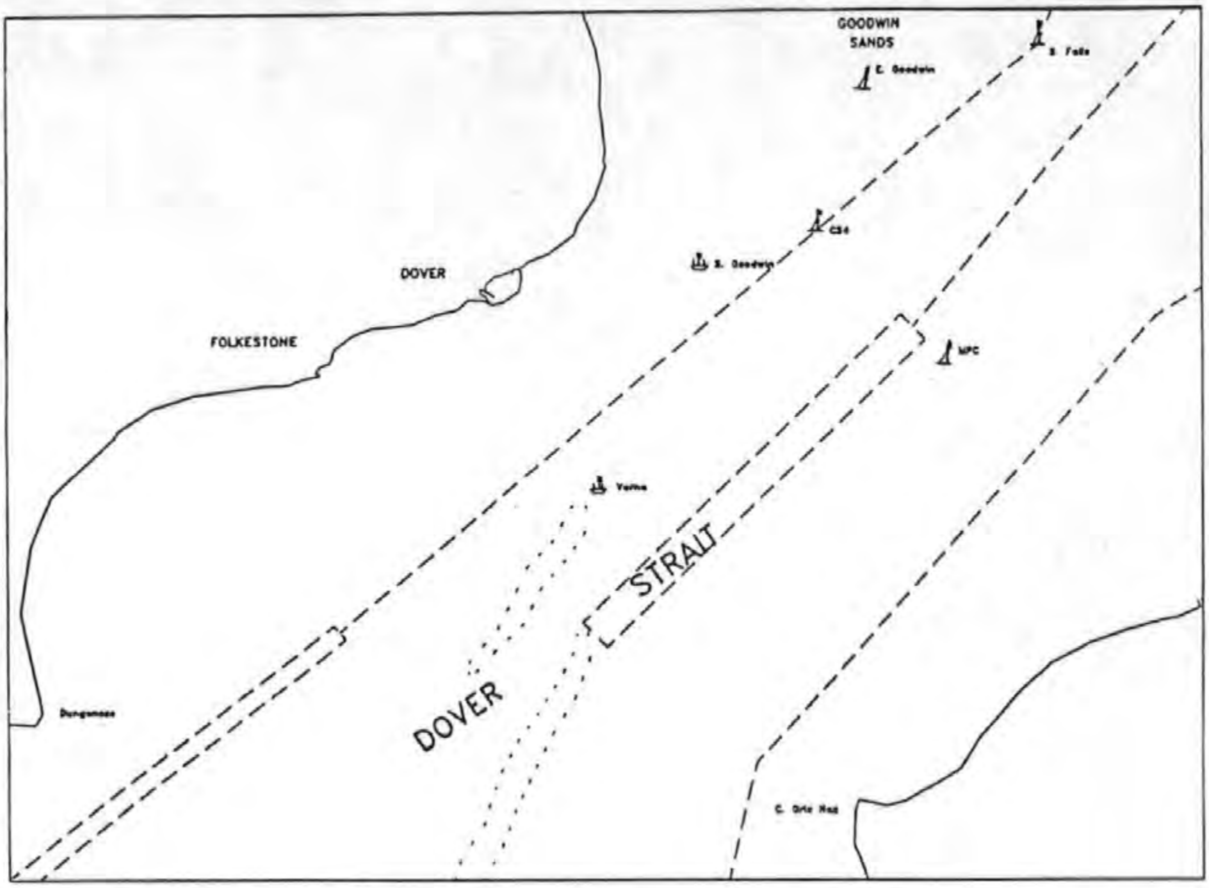


Fig.6.1 The Dover Strait

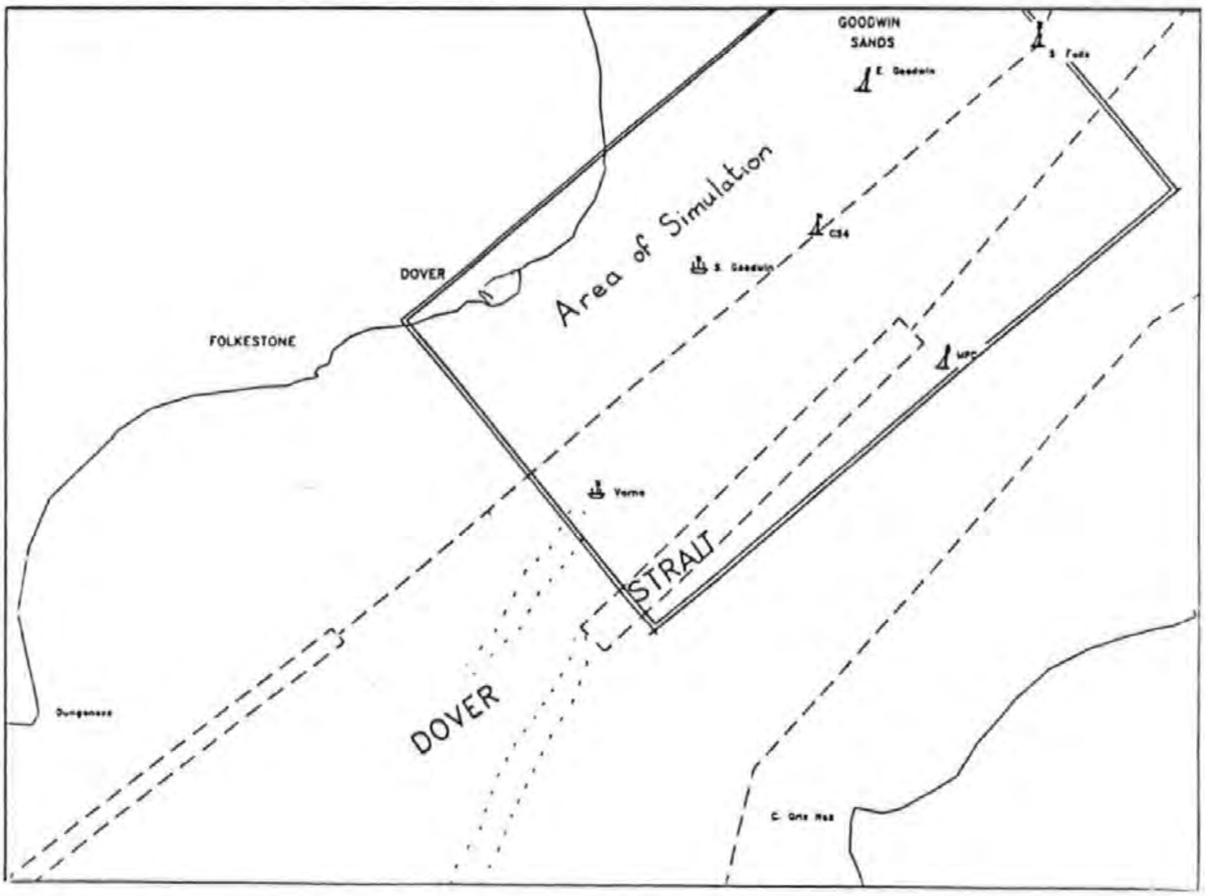


Fig.6.2 The orientation of the navigation grid

memory. Since each route was represented by its own grid pattern and there were 12 different routes, then the one mile square elements required a total of 2400 records to store all the relevant information. Clearly an increase in accuracy through a reduction in the size of the elements to 0.5 miles square would have quadrupled the required number of records.

6.3.4.2 The determination of the most frequently used routes

The initial method used to determine the most frequently used routes was to surround the area of interest (the main lane) with artificial "gates" one nautical mile apart. The term "gate" was used to describe a fixed line of predetermined length and orientation, through which the time at which a vessel crossed could be determined easily. The "gates" ran up both boundaries of the main lane and across the main lane at the Varne, the CS4 buoy and the South Falls. Vessels were then considered in turn, the track consisting of a sequence of "gates" through which the vessel had passed and the corresponding times. Ships travelling across the routing scheme normally passed through two "gates", whilst those navigating down the routing scheme usually passed through three. From this analysis twelve most frequently used routes were obtained.

The gate-counting method was decided to be restrictive in that the actual point at which an alteration of course took place was not necessarily identified. This was of particular importance when attempting to determine the courses steered by the ferries, which through compliance with Rule 10c were often forced to make several broad alterations. It was decided that the obvious method was to plot all the tracks through the area by recording the grid coordinate and the corresponding time at each significant alteration of course. By projecting the 24 mile radar film directly onto the grid, the position was easily determined, with an estimated accuracy of ∓ 0.2 mile.

Figures 6.3a and 6.3b show the generated tracks of two days traffic through the main lane. Vessels that stayed in the English Inshore Zone and never entered the main lane were not included, nor were any vessels that exhibited unusual actions, such as fishing boats, naval craft, hydrofoils and hovercraft. The main-lane traffic was detected easily by the high density of horizontally running tracks. It appeared at first that little could be deduced from the apparently random nature of the crossing traffic, but when the traffic was categorized by the vessels' destination, then patterns began to emerge. It was found that the routes could be rationalized in exactly the same way. Thus all ferries from Boulogne, Calais and Zeebrugge to Dover made use of the same grid. This assumption was based on the premise that most of the ferries displayed approximately the same dynamical characteristics and as a consequence their home passage was dependent solely on their position in the scheme. For example a Boulogne - Dover ferry forced to alter course a substantial distance to starboard could well have found itself in a position, in the routing scheme, normally occupied by a Calais - Dover ferry. It would not then have tried to alter back onto the previously specified course, which would have wasted more valuable time, but would have followed the most efficient route from its displaced position to Dover

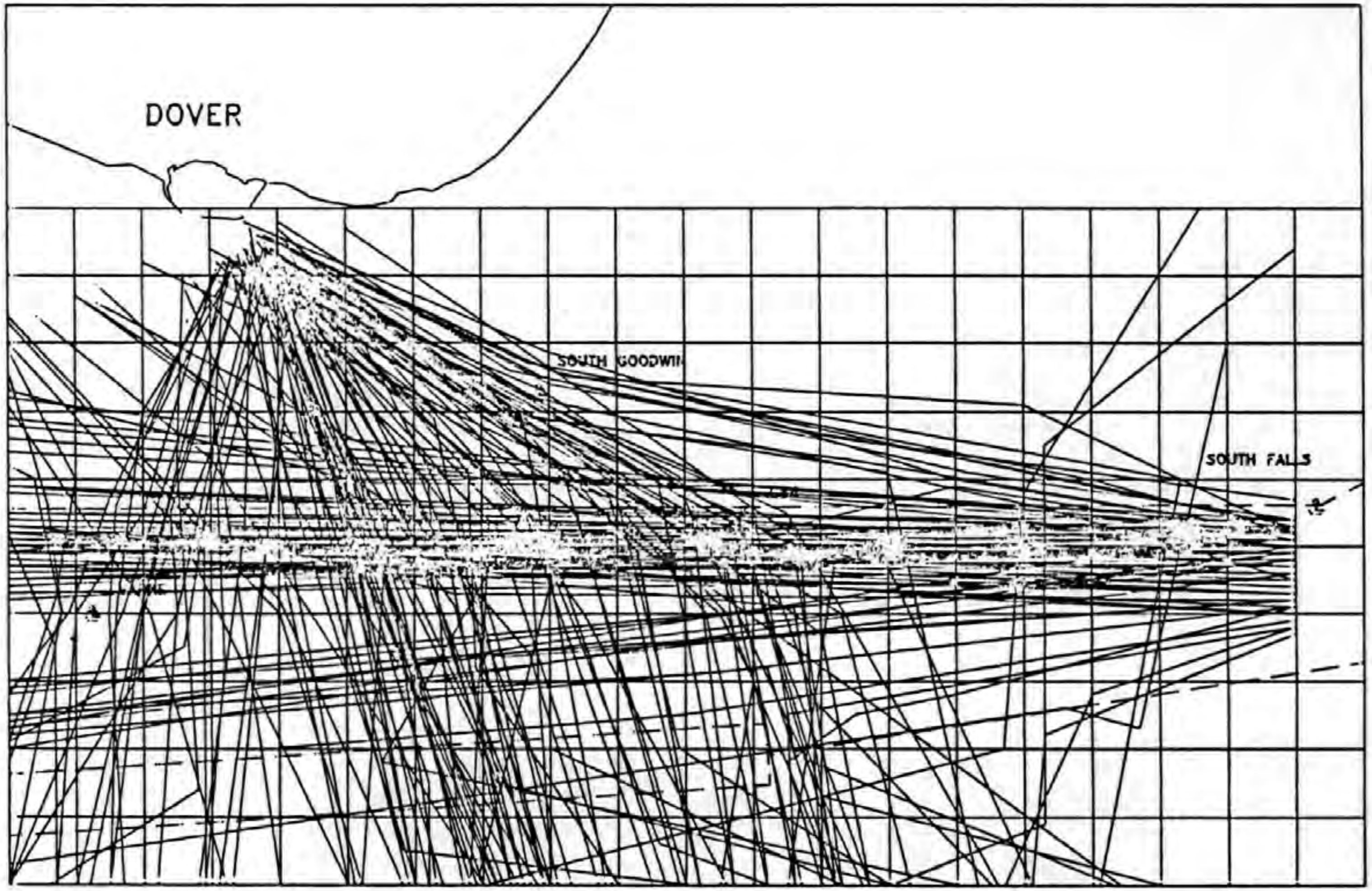


Fig 6.3a Generated tracks of observed traffic for Day 3

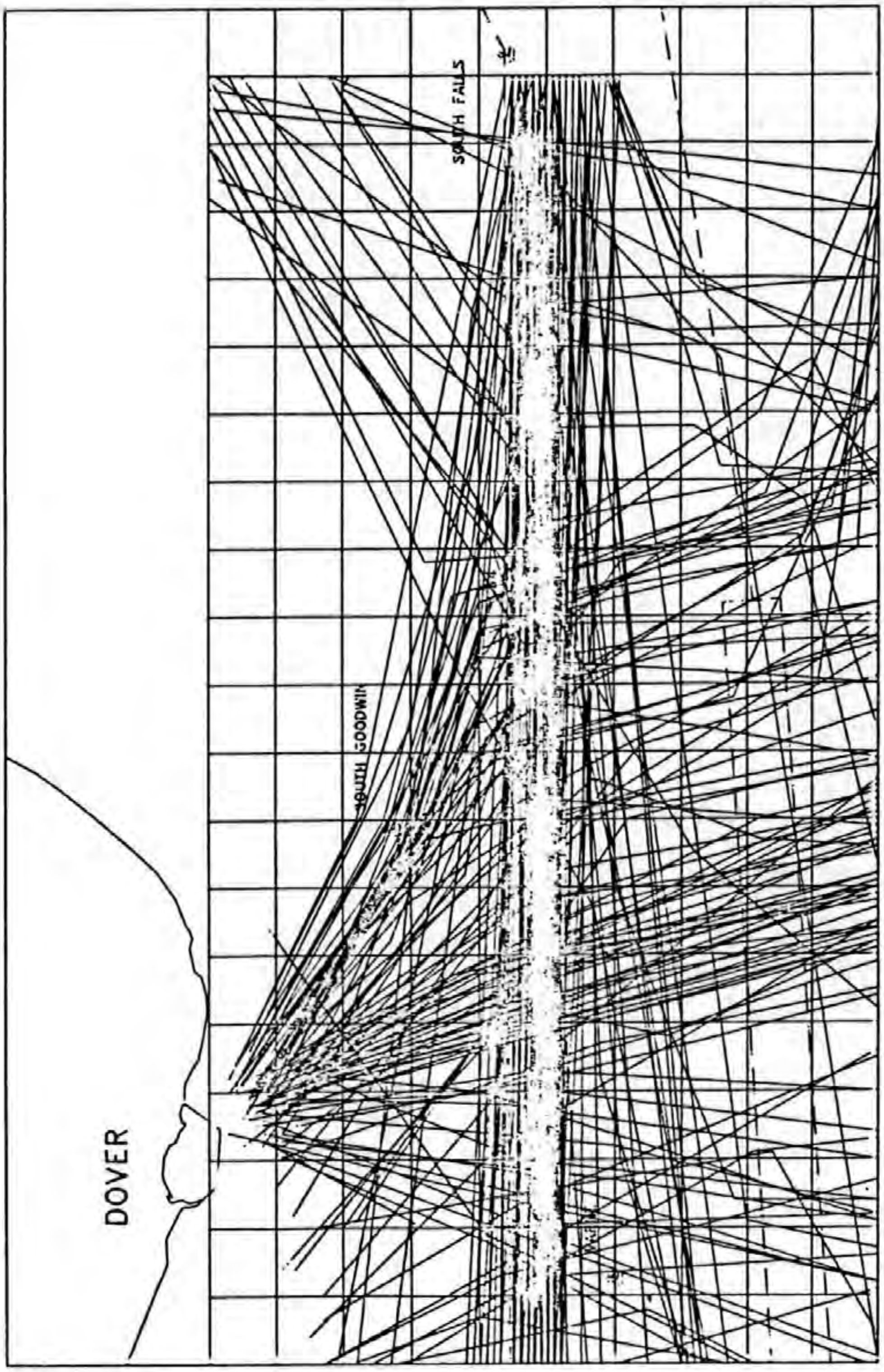


Fig 6.3b Generated tracks of observed traffic for Day 4

or the same route as followed by the Calais - Dover ferry.

6.3.4.4 Route implementation

Given that every route was described by a unique grid, then the next problem was to determine the means by which a vessel in a particular element within that grid was assigned its desired course. Thus each route has a unique set of records, with each record relating to an individual grid element. When a vessel entered a new grid element then the corresponding record was interrogated to determine the new desired course. Initially each record consisted solely of a course. Figures 6.4a and 6.4b show two examples of the resulting grids for vessels navigating down the routing scheme and for ferries to Dover. The method proved to be unsuitable however, with navigational alterations being implemented as a series of changes at subsequent elements, resulting often in stepped tracks as opposed to a quicker and smoother change of course. Further difficulties were experienced when realistically attempting to avoid stationary objects such as buoys.

It was decided that the use of orientation points (O.P.) would solve the problem, but for the reasons discussed in 6.3.3 they could not be used on their own. The records were modified so that the first value indicated the type of record, whilst the subsequent values were either a simple desired course or the identity of the O.P. from which the desired course was calculated. This use of a whole record allocated to each element allowed a great deal of flexibility in that a random variation to the desired course could also be introduced without

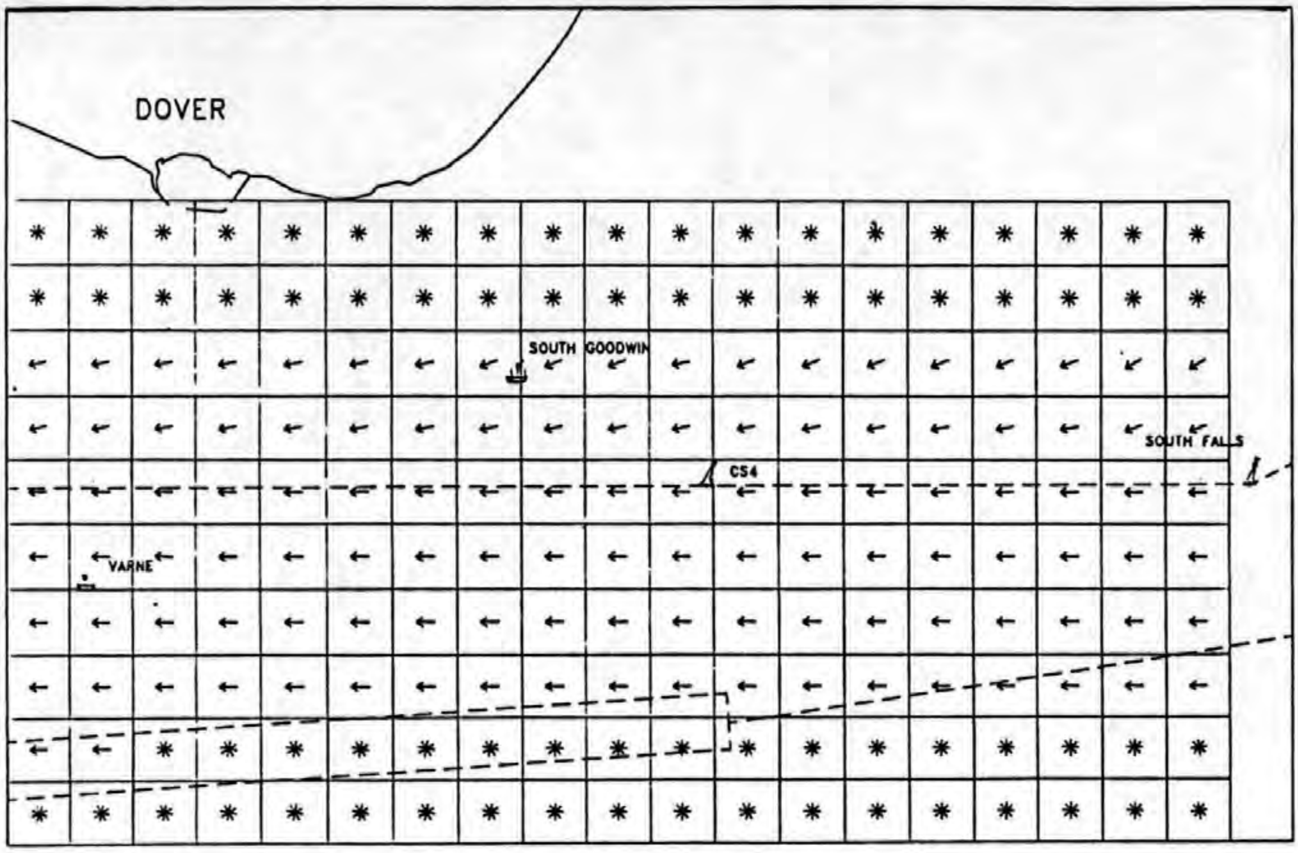


Fig.6.4a Example of grid courses for through traffic

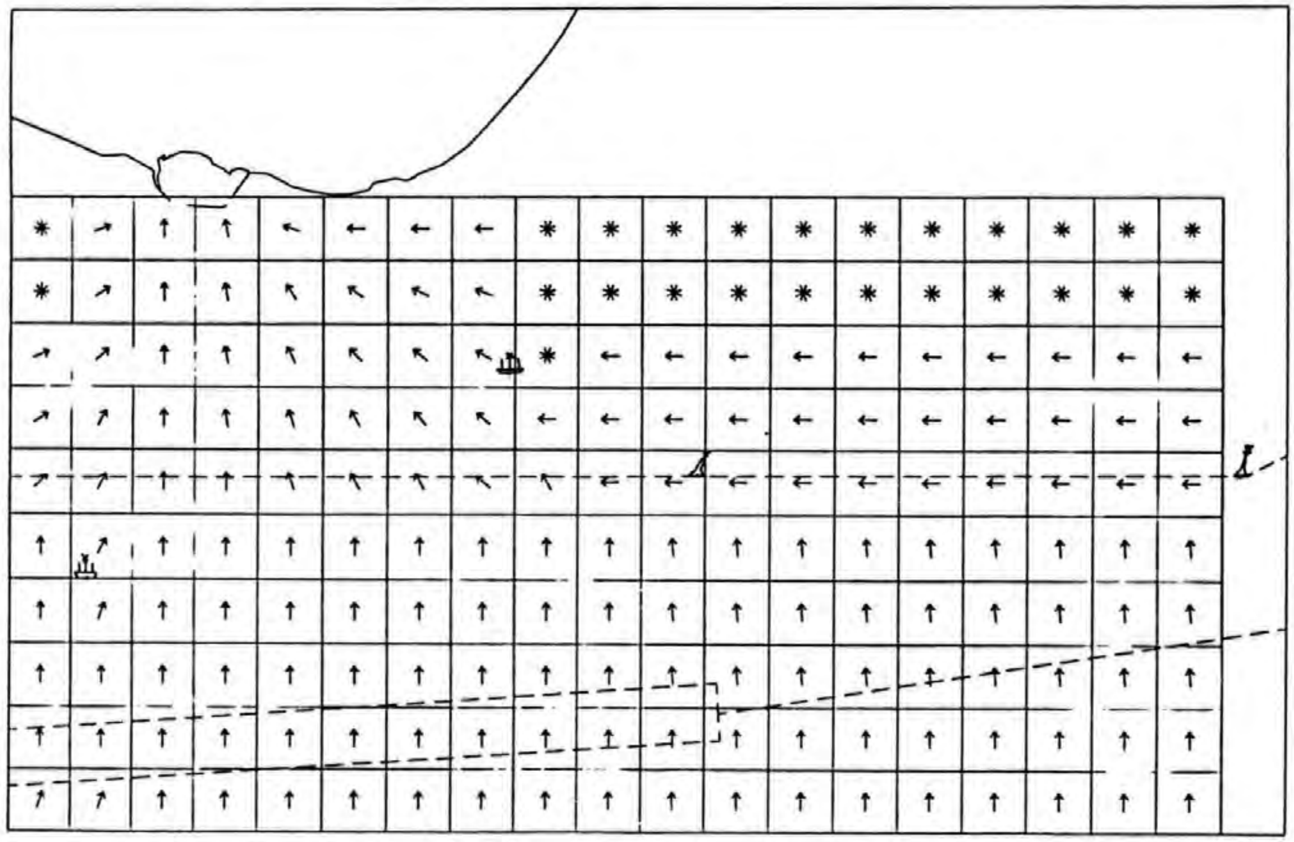


Fig.6.4b Example of grid courses for ferries to Dover

difficulty.

Courses were then modified by the addition of a specified variation of angle, which could be to port or to starboard, from which the desired course was then calculated. The variation was obtained by using a random number within the range 0 to 1, selected from a specified normal or uniform distribution generator (NAG routines E05CAF or E04BBF respectively). The generated distribution was not truly random but pseudo-random since the routine used an integer number as a seed to generate the number, with each seed producing the same, unique number. This meant that by carefully selecting the value of the seed, a unique random number could be generated for each individual vessel, but of more importance the same variation could be applied over a section of the route rather than changing at each new element.

O.P.s were followed by two values, which in this case represented the possible variation in the O.P. position to the port and starboard. Thus the desired course to the O.P. was found initially and then the variation calculated and applied (Fig.6.5).

6.4 Buoys and other stationary objects

The initial approach used for avoiding buoys and other stationary objects was to treat them as stationary ships, for which own-ship had a special domain. Thus a vessel determined whether a buoy was threatening in exactly the same way as if the buoy was another target. The procedure of testing against a domain belonging to the own-ship meant however that there was no method of discriminating between different objects. A more realistic plan of action was for the stationary objects to have their own domains, which the vessels attempted not to infringe. A vessel was said then to be infringing a buoys domain if its miss distance was less than the specified domain size for that buoy. Using this plan the different threats posed by, for instance, an oil-rig, buoy or very slowly moving barge could be distinguished. Goodwin and Kemp (1980) studied the domains of stationary objects and for most areas of sea concluded that the buoy domain was usually constant at approximately one cable. It was decided therefore that this value was a reasonable value to use for buoys in the simulation. Each buoy also had a time associated with it that related to the time at which a mariner would wish to alter course for that buoy. Therefore the procedure was exactly the same as for a target, in that a buoy was checked for infringement if the vessel's T.C.P.A. was less than the criteria for the buoy. If the buoy was infringed then the vessel altered course, at half the usual rate, until the domain was no longer infringed.

It was noticeable however, from the analysis of the radar film, that mariners did not appear to treat all buoys in a similar fashion. There was a substantial difference in the observed miss distances to the Varne light-vessel with that observed at the CS4 buoy. This was not essentially due to the physical dissimilarities between the light-vessels and the buoys but was a function of the usage of the buoy. The Varne light-vessel marked the north-eastern extremity of the Varne sandbank, while the CS4 buoy indicated the northern boundary of the main lane. The initial solution appeared to be in the use of larger domains for buoys or light-vessels marking dangerous sand-banks or other natural obstructions. The difficulty in using the larger domain was however that different mariners approached the Varne with different levels of apprehension. Whilst through traffic tried always to give the Varne light-vessel a wide berth, cross-channel ferries were observed regularly to pass within a few cables of the light-vessel. Even through traffic, when forced through collision avoidance, passed much closer, shrinking effectively the size of the domain. The distinction had to be made between navigation and collision avoidance. The domain, by its definition, is not an aid to navigation but is a means of determining when a collision avoidance manoeuvre is necessary.

The solution, in the model, was to use the same domain size of 0.1 n.miles for all buoys and light-vessels, but to navigate the vessel, well before domain infringement would have occurred, in a manner so as not to come within the limits normally portrayed by that obstruction. This was felt to be realistic and the procedure used practically at sea. The stationary objects were specified as O.P.s, from which a mariner determined a course to clear rather than to hit. This concept was incorporated in the model by using the grid elements around a stationary object to navigate a vessel safely past that object.The format of the record required for these grid elements was different to the usual O.P. record and was indicated again by the first value in the record. In this case the distribution on either side of the object from which the own-ship determined the desired course was in the form of four values specifying two bands of permitted courses (Fig.6.6). It can be seen that the navigational course alterations needed to avoid stationary objects were incorporated in the grid and as such were different for each type of route.

A difficulty experienced in the use of stationary objects as O.P.s was found when a vessel had to then change to the subsequent O.P. or take a new desired course. The reason was that the course was set so as to miss the stationary object, but since the next desired course had to be set before that object was encountered (to ensure that a vessel did not try to alter back on itself) it was found that the miss distance was sometimes reduced by the subsequent alteration, thus defeating the original purpose. A solution was found by introducing an area around stationary objects, in which vessels retained their previously assigned courses. Thus a vessel navigated to miss a stationary object by a randomly generated amount, then on approaching the object retained its previously assigned heading and once past the object determined the new designated heading.

6.5 Land and sand-banks

In the following section both the words "land" and "sand-bank" have been replaced by the more meaningful word "relevant contour" (R.C.). The R.C. was defined then as the boundary marking the area in which a vessel would feel restrained by draught. Although its shape clearly changed as the depth of water varies, due to the tidal cycle, the tide was not incorporated into the simulation. Consequently since all

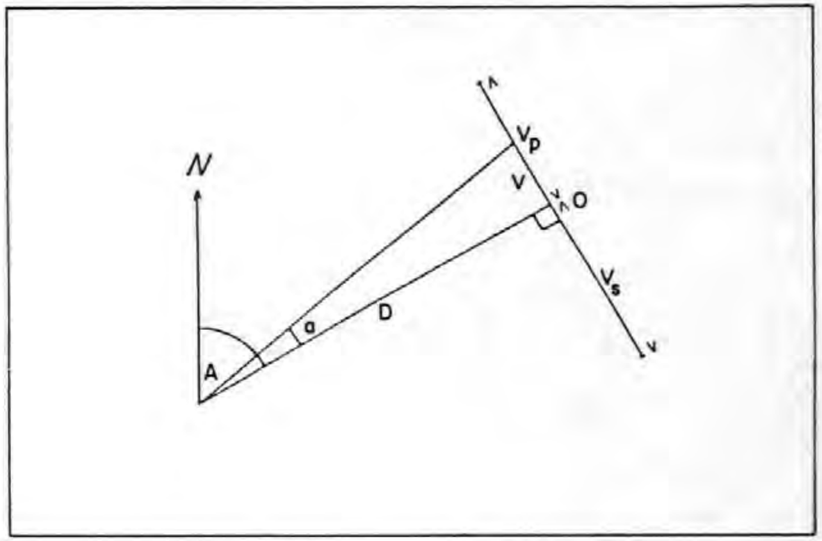


Fig. 6.5 The calculation of desired course to a specified O.P. and with a specified port and starboard passing variation

Where: O is the position of O.P.
V_p is the variation to port
V_s is the variation to starboard
D is the distance between own-ship and the O.P.
A is the bearing of the O.P. from own-ship
a is the resulting variation

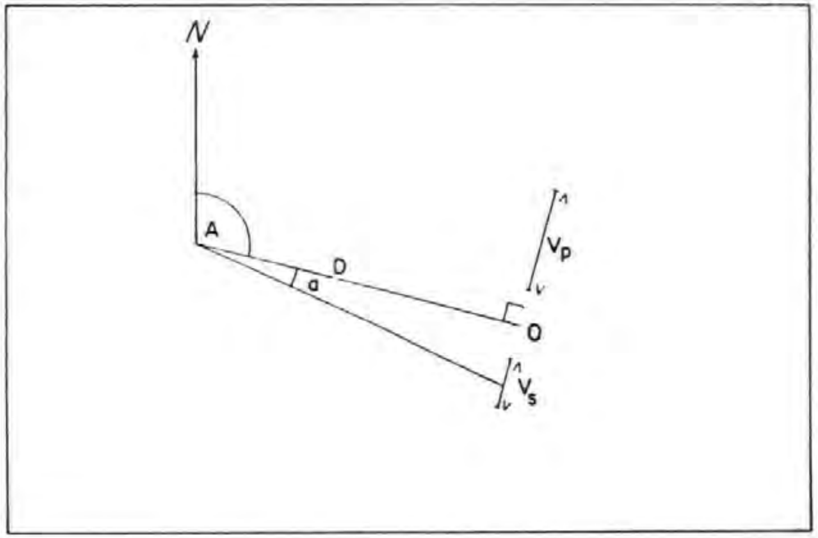


Fig. 6.6 The calculation of desired course to clear a buoy within a specified range on either side

Where: O is the buoy position
V_p is the specified port variation
V_s is the specified starboard variation
D is the distance between own-ship and the buoy
A is the bearing of the buoy from own-ship
a is the resulting variation

depths were obtained from the admiralty chart (No. 1610), on which all depths are below chart datum, a correction equal to a mid-tidal value was used.

The initial method used to avoid the R.C. was to treat it as a set of stationary targets each with their own special domain (Davis, 1981). The only difference to the approach used by Davis was that every point was assigned a time, as opposed to a distance, at which the mariner alters course to avoid the R.C.. Again as in the Davis model a "look ahead" algorithm was devised to prevent vessels following the curve on concave contours. Thus on infringement of the time criteria the contour was scanned and a course eventually steered to miss the domain of the most pronounced point within 6 n.miles of own-ship. It was decided however that this method was both costly in computer time and memory.

A solution was found in the same manner as for the stationary objects. That is the emphasis should not be on collision avoidance of the R.C. but on the navigation serving as a means of preventing that situation arising in the first place. The use of domains in avoiding the R.C. was effectively saying that mariners ignore land and sand-banks until they come within range. This was clearly a fallacious argument because all mariners have access to a high quality chart of the area, in which the natural obstacles are clearly high-lighted. A mariner was assumed to set his course so as never to get into a situation where he was restrained by his draught.

The navigation grid was designed to follow the average paths of vessels in each route type. The analysis also showed quite clearly that mariners were reluctant to sacrifice sea-room to starboard and hence aimed to keep the R.C. well on the starboard side. It also demonstrated, in a couple of cases, how mariners faced with a give-way encounter, whilst being restricted by their R.C. tended either to slow down, sometimes undertake a non-standard manoeuvre or stand-on. It was decided therefore that when a vessel was in the vicinity of its R.C. that a desired course would be given but rather than then allowing a distribution of course variation to both sides, two limiting courses past which a vessel was not permitted to alter were included. Hence in an encounter situation, if a vessel found that an alteration of course resulted in its breaking one of the limits then another collision avoidance procedure was adopted, which depending on the circumstances either dictated that the own-ship slowed down or that the target altered course instead.

To conclude, the functions of the navigation grid at any element were determined by the first value of the record belonging to that element. The functions pertaining to this first value (ITYPE) were as follows:

a) ITYPE = 0 - a course was selected with a normal distribution randomly selected to be within constraints on either side;

b) ITYPE = 1 - an orientation point was selected. Its identification enables the position to be determined from two O.P. arrays which contained the X and Y coordinates respectively. The desired course was then found by firstly calculating the bearing of the O.P. and then applying a variation to that angle using either a normal or a uniform distribution (indicated in the record);

c) ITYPE = 2 - identical to "b" except that the O.P. was a stationary object and the aim was therefore in missing as opposed to hitting the selected position. The record described a permitted band of courses available on either side of the object with the type of distribution that was to be applied;

d) ITYPE = 3 - used in the vicinity of a vessels relevant contour (R.C.). Described the desired course and the bearing limits on either side, outside of which a vessel was not permitted to alter;

e) ITYPE = 4 - a vessel retained its previously obtained desired course;

f) ITYPE = 5 - used when a vessel reaches land-fall. In which case rather than attempting to avoid the land, the vessel stopped and was no longer considered in the simulation.

6.6 Vessel types

The next requirement was to sub-divide the types of vessels in the area into groups representative of their characteristics. The diversity of vessels using the Dover Strait, however, is almost unlimited. This made the categorization of the vessels into types a difficult task. Some of the inherent problems were reduced through the decision not to include inshore traffic in the simulation (those not entering the Traffic Separation Scheme). Other vessels excluded were those that exhibited unusual navigating behaviour. Fishing vessels were identified by their irregular tracks whilst hydrographic surveying vessels tended to follow a regular scanning motion. Another set of vessels to be rejected were Royal Navy vessels because of their unusual manoeuvring characteristics and their tendency to navigate in formation. The ideal situation then would have been to sub-divide the remaining vessels by their dynamical characteristics. The dynamics included the normal operating speeds and manoeuvring behaviour. Depending on the complexity of the model, the dynamics are a function of the operating speed, power-to-weight ratio, length, dead weight tonnage and other parameters. Clearly the only parameters that could be determined directly from the radar film were the speed and an approximation of the size of the vessel. It was decided to categorize the vessels as follows:

a) Type 1 15 - 20 knt.;

b) Type 2 10 - 15 knt.;

c) Type 3 less than 10 knt.;

d) Type 4 greater than 20 knt.;

e) Type 5 all ferries.

It is a valid argument that a V.L.C.C. steaming at 14 knt. is unlikely to display similar characteristics to a general cargo of 2000 dwt. steaming at the same speed. To have drawn any conclusions, other than the operating speed, would have necessitated an estimation of the size of the vessel from the dimensions of the echo. There are however many influences on the size of the radar return echo. These include the distance from the receiver, the aspect, the sea state and the general atmospheric conditions. Furthermore, even if the size could have been determined reasonably from the echo size, large variations can exist in the types of vessels of the same size and speed. It was decided therefore that the best solution was to categorize vessels solely by speed.

The one exception to this generalization was the fifth ship type, the crossing ferry. Although their speed range could put them in the Type 4 or the Type 1 range, their manoeuvrability alone put them in a class of their own. Their type was determined by the origin and destination of their voyage and so the problem of having to determine the size from the echo did not arise. A further reason for categorizing the ferries separately was because of their unique interactions with other vessels. These are dealt with later in this chapter.

6.7 Special rules for the Area simulation

6.7.1 The Routing Scheme boundaries

Observations of the radar film and feed-back from the partially mariner controlled simulation indicated that mariners navigating down the main lane had definite reservations about crossing the routing scheme boundaries. This was as would be expected from mariners following the Collision Regulations (Rule 10). The provision is made that vessels may cross if forced to do so through the threat of a collision. If a lateral displacement from the routing scheme was observed then vessels altered back at an angle that was a compromise between entering at as small an angle as possible and staying in the Inshore Zone for the minimum period of time. The simulator exercise for the Dover Strait was studied specifically to consider the angle at which mariners re-entered the scheme (the angle of repose). Figures 6.7a and 6.7b show the results of the analysis of the simulator data for a total of 44 manoeuvres out of the routing scheme. It can be seen that there was little correlation between the angle of repose and the lateral deviation from the lane boundary or distance into the E.I.T.Z. (Figure 6.7a). The correlation coefficient of 0.36 for the angle of repose against the total lateral deviation suggests that the mariner is more concerned with the total lateral displacement resulting from his manoeuvre (Figure 6.7b) than with the distance that he is forced to manoeuvre into the E.I.T.Z.. This would suggest that his main worry was one of the loss in time due to the manoeuvre than the dangerous aspect of navigating through the E.I.T.Z.. It was decided that the manner in which vessels navigated down the main lane was sufficiently flexible to return wayward vessels to the main lane. Since through vessels used either an O.P. to the north-west or the south-west of Varne, depending on their route, then any lateral deviation was automatically compensated for by the resulting change in the bearing of the O.P..

The initial aim of the vessel to remain in the routing scheme was reflected in the desired course, that was determined from the directions grid. Similarly the angle at which a vessel, that found itself in the Inshore Zone, returned to the scheme was obtained from the grid. Only two observations of vessels infringing the southern boundary of the main lane were noted from the radar film, whilst none occurred in the simulator exercises.

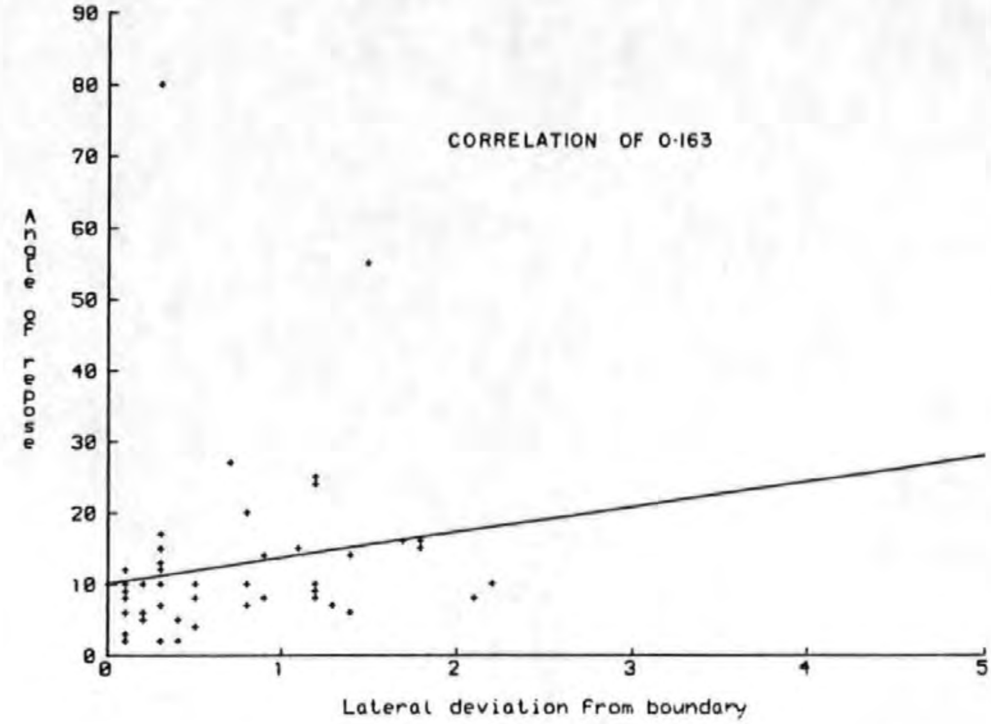


Fig.6.7a Relationship between the angle of repose and the lateral deviation from the lane boundary

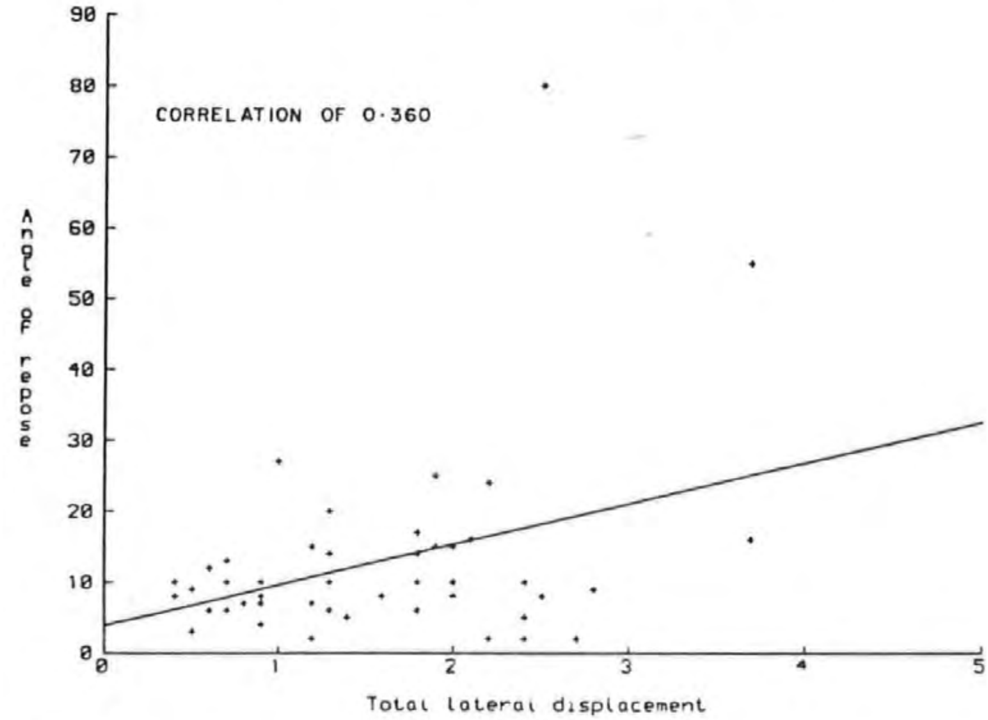


Fig.6.7b Relationship between the angle of repose and the total lateral deviation

The direction grid stops through vessels crossing the main lane boundary unless due to collision avoidance. A reluctance to cross the boundary was noted also when considering the type of collision alteration to make for a threatening vessel. It was noticed that when a vessel was considering on which side to overtake a vessel and was on or near to the northern boundary that it rarely manoeuvred to starboard. Hence there existed a preference to remain in the main lane as opposed to leaving sea room to starboard. This was implemented in the model in exactly the same manner.

Another trait that emerged was that a vessel in a give-way crossing situation, that had already been forced to manoeuvre out of the main lane, was more likely to either slow down or stand-on than alter course again to starboard, which would have increased further the lateral displacement from the boundary. This was implemented again by considering the position of the vessel when forced to make its decision.

6.7.2 Ferries

Another peculiarity noted from the observation of ferries bound for the Continent, was their tendency to give-way to main lane traffic when according to the Collision Regulations they were the stand-on vessels. This action was generally executed in good time and was thought to be more the case of a precautionary navigation alteration to aim for "the gap" than a collision avoidance manoeuvre. As such the facility for ferries to alter course, as stand-on vessels, when threatened was not incorporated, but the emphasis was changed so that the manoeuvre became one for navigational purposes instead. This was achieved by allowing a ferry to alter course to cross the routing scheme at a right-angle as soon as it was clear to do so and the ferry was within two miles of the boundary. Thus in the simulation if the ferry was crossing to Calais, Dunkerque or Boulogne, as soon as it came within two miles of the boundary, then the new course of 180 degrees was tested for domain infringement with main lane traffic. If no vessels were threatening then a new desired course of 180 degrees replaced that indicated by the grid. If however the ferry was destined for one of the more northerly European ports then the manoeuvre was not allowed because in practice the mariners navigated at least past the CS4 buoy before crossing.

6.7.3 Overtaking

On comparing the values obtained by Curtis (1980), the observed track separations between main lane overtaking vessels were generally unsafe in poor visibility. The situation used by Curtis to obtain his reaction time experimentally and subsequently to calculate minimum safe overtaking distances, in which a main lane vessel swung suddenly across the bow of a paralleling vessel, was observed by the author to occur occasionally in good visibility. As Curtis has shown, the small distances between vessels in overtaking encounters can result in rapidly developing emergency procedures and as a consequence result in some very close approaches between the vessels involved. This was observed several times in the computer simulation, when a vessel navigating down the main lane was forced, through a collision avoidance manoeuvre for a crossing ferry, to manoeuvre across the bow of a neighbouring through vessel. It was found also, from feed-back from the simulation of the radar display exercises that in such a situation the vessel forced to alter across the bow of another would firstly attempt radio communication to transmit his intentions. It was decided that in this situation the vessel would have the facility, depending on the proximity of the following vessel, to slow down as opposed to altering course to starboard.

6.7.4 Progressive multi-ship encounters

Clearly when considering the Dover Strait one is certain to observe many multi-ship encounters. When more than two vessels are heading for the same point then collision avoidance is straight forward and in general the encounter is resolved by a rotation to starboard around the collision point. In a similar fashion to a two ship encounter the situation becomes more difficult when considering multi-ship encounters between vessels where a substantial degree of contribution, negative or positive. The most difficult situation however, and one that the computer simulation proved unable to resolve adaquately, without the introduction of special procedures, was the situation in which only one vessel was initially threatening the give-way vessel, but subsequent action by the give-way vessel resulted in a previously innocuous vessel suddenly becoming a threatening one.

Figure 6.8 shows a typical situation in which such a problem was frequently observed to occur. Ship A is a ferry crossing to Dover and Ship B and C are through vessels. Initially B is threatening A whilst C is passing well clear. This diagram and the following diagram (Figure 6.9) show three vessels A, B and C at successive periods in time. Thus vessel A is shown as A1, A2 and A3 relating to its position at times t=t1, t=t2 and t=t3 respectively. For each period in time the relative velocity of each of the other two vessels, B and C, have been depicted by a fine line. At time t=t1, A decides to alter course for B and proceeds though successive iterations to bring the ship round to starboard. At time t=t2 vessel B is no longer infringing A´s domain, but it is not yet on A´s port bow and the alteration is not yet completed. At time t=t3 vessel C is suddenly threatening the domain of A and due to the increasing relative velocity, due to the two tending towards reciprocal courses, the T.C.P.A. has been dramatically reduced. The conventional response by the model required A to take further evasive action to starboard for C. In many runs it was found however that this necessitated an alteration of more than 90 degrees from the desired course, which was clearly inefficient and unlikely to occur in practice.

No complete solution was found as in the worst situation of this kind a mariner would be required to look ahead to a level that would have been impractical to duplicate in the simulation. Two realistic procedures were however adopted that in the first case aimed to reduce the frequency of occurrence of the situation and in the second produced an alternative means of correcting the situation. The first means involved a crude form of looking ahead and depending on the situation taking early action if appropriate. The look ahead facility was implemented as follows: at a time 3 minutes before the R.D.R.R. becames equal to ship A´s time criterion the new course required to bring B onto A´s port bow was determined, all other vessels detected by A were then considered for domain infringement given the new course. If any were threatening then A delayed altering course for B until the R.D.R.R. becomes equal to the time criterion and it was left with no alternative.

The second procedure involved a reduction in the magnitude of the alteration. If a vessel has no option but to alter course then the requirement of further alteration from the new target can be minimised by allowing the give way vessel to firstly stop altering away as soon as the domain is cleared, and secondly to start coming back on to course at a reduced miss distance astern of the original threatening vessel B.

The introduction of these two facilities had a marked effect on the efficiency of such encounter avoiding action for the situation in which the give-way vessel was crossing. The situation for the overtaking vessel however introduced a completely different problem. Figure 6.9 shows a typical crossing encounter with ship (A) in this situation a main-lane vessel is give-way to a ferry (B) bound for Calais. A has a vessel (C) on its starboard side on a parallel course which may or may not be faster than A. The important fact is that on taking collision avoidance action the vessel C is put into sudden difficulties which in some cases leaves ship C with very little time to take evasive action. The partial solution to this problem was a gross simplification of the algorithm conceived by Curtis in determining safe overtaking distances for vessels. In this case however the onus was not on the overtaking vessel to pass at a safe distance, but for ship A to slow down as opposed to altering course in a dangerous situation.

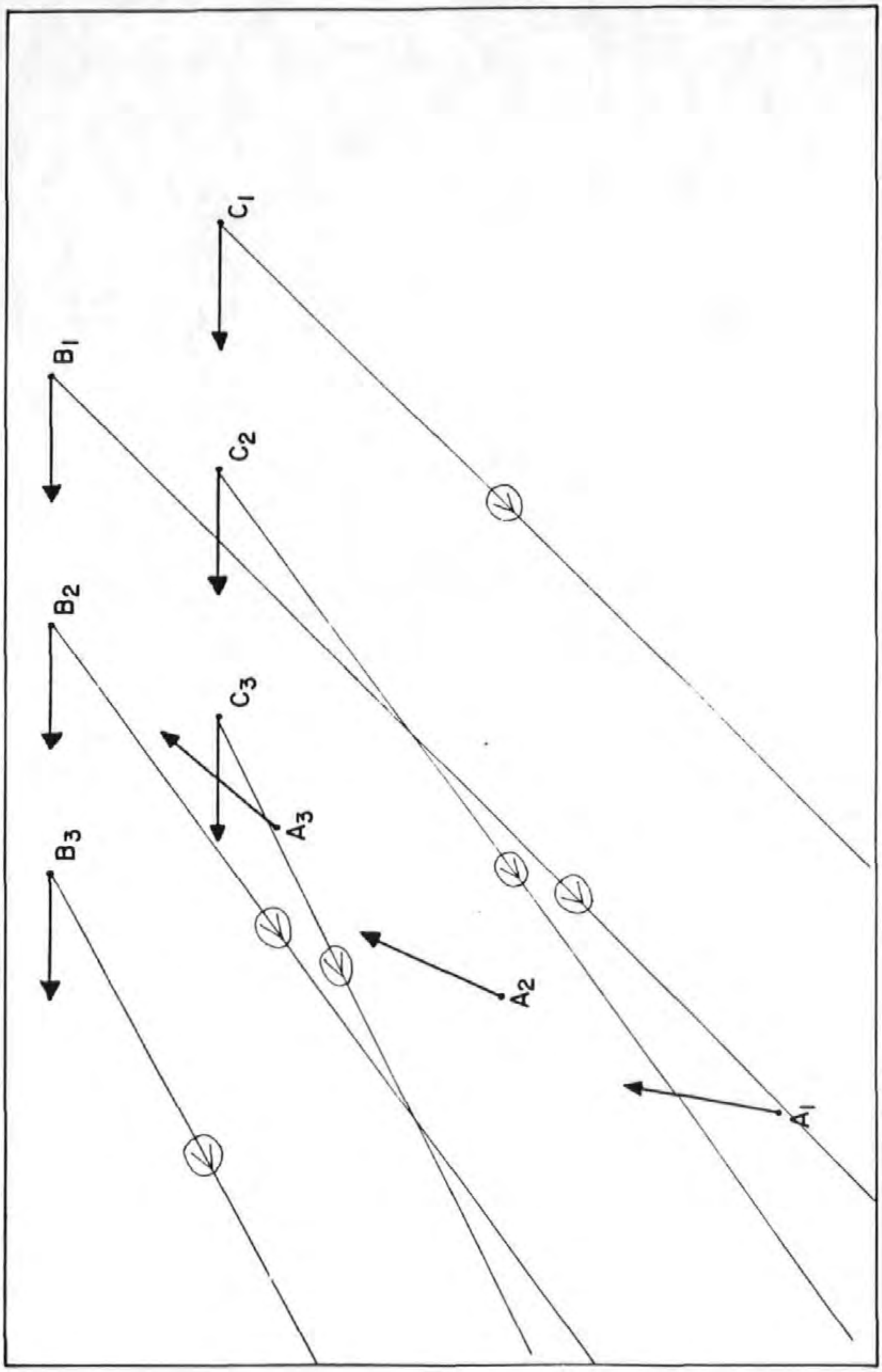


Fig. 6·8 Crossing ferry (A) shown altering course initially for through vessel (B) and being forced subsequently into a a near miss with through vessel (C)

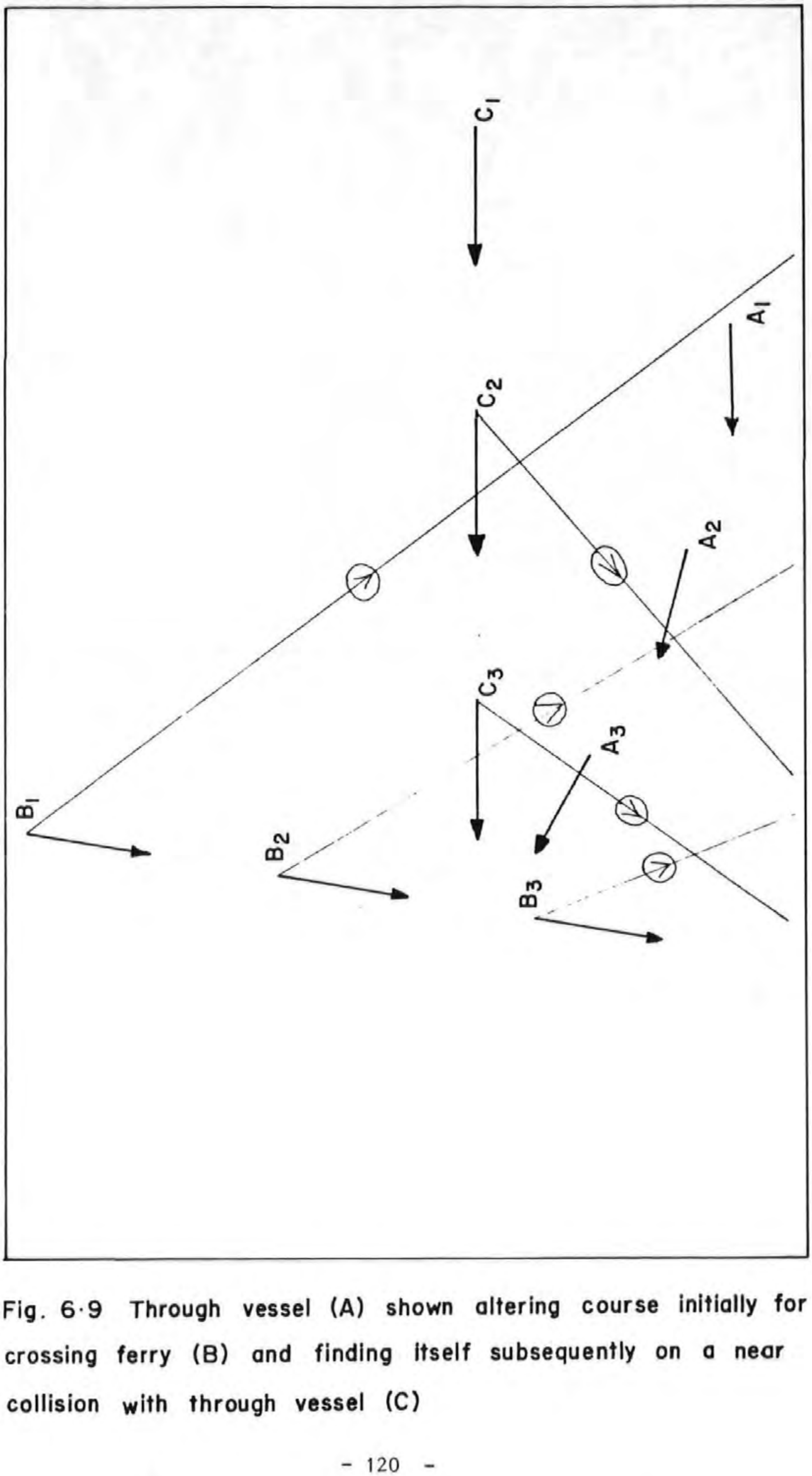


Fig. 6·9 Through vessel (A) shown altering course initially for crossing ferry (B) and finding itself subsequently on a near collision with through vessel (C)

Chapter 7 The validation

7.1 The design and control of simulation runs

7.1.1 The initialisation

Perhaps the most important single stage in the development of a realistic model of any system is the setting up of the initial conditions. It is upon these initial parameters that the subsequent simulation is developed and as a consequence any error or misjudgement in the starting condition can result easily in that error being compounded throughout the course of the run. All the data for the runs of the computer simulation of the Dover Strait traffic system were determined from the analysis of the 24 mile radar film. Although the main purpose of the analysis was the determination of the most frequently used routes and the practical navigation within those routes, enough information was obtained to enable assessment of flow rates, speed distributions and lateral distributions across the vessels routes.

There were four main sets of data inputs to the system. They were:

a) the data relevant to the individual ships, comprising the starting times, positions and corresponding navigation route and ship type;

b) the information relating to the navigation of the vessel, which was contained mainly in the grid but also required the positions of the buoys and any referenced way-points;

c) the parameters describing the different ship types, which consisted of the speed range, the maximum rate of alteration, the domain radii and the R.D.R.R. criteria;

d) the physical limits, outside of which vessels were no longer considered by the simulation, and the time limits of the computer run, which were defined by the starting and finishing times.

7.1.1.1 The use of observed starting times and positions

The most obvious means of setting-up the initial conditions was to use all the information available in the radar film analysis to provide, as nearly as possible, the same conditions in the simulation. The main advantage of this approach was that it provided the most suitable means of validating the model, with the smallest possible number of discrepancies allowing a reasonably unbiased comparison between the observed and simulated situations. Since all the vessels, over the two days continuous plotting, had been assigned a route and from their velocity, a vessel type, all that remained was to ascertain their starting position and time.

7.1.1.2 The simulation of a randomly generated sample

Although the direct use of historical data as a means of setting-up the starting conditions allowed the most accurate assessment of the variation between the simulated and the observed results, it clearly had no means of generating a random sample of mariners' actions, necessary for any form of predictive or analytical work. It was assumed that the number of vessels per day for each navigation route remained constant and these were determined from the radar film.

There then remained three main areas in which a random sample might be determined: the inter-arrival time distribution of vessels entering the scheme; the distribution of ships' speeds and the positional distribution of vessels entering the area.

<u>The rate of arrival.</u> To determine the starting times of vessels it was necessary firstly to determine some property of the distribution of times. Queueing theory provides two means of considering arrival time data: the first is to consider the distribution of the arrival rates and the second the distribution of the inter-arrival times. There existed however two main types of traffic using the Dover Strait and both displaying different rates of arrival properties. These two could best be described as scheduled and unscheduled or random traffic. Clearly ferries were categorized in the former whilst the bulk of the main lane traffic was assigned to the latter. The use of either time-tables for vessels leaving Dover or Folkestone and historical data directly for ferries from the Continent was justified as the nature of the scheduling meant little daily variation. The term "random" relating to non-ferry traffic was a simplification of the system and ignored the effects of the tidal cycle on the departure of vessels from ports "feeding" the Strait. It was necessitated however because any queueing theory assumes all traffic to be of a random nature.

There existed then two means of utilizing the observed distribution of inter-arrival times to obtain a random sample of vessels. The first was to sample directly from the observed distribution and the second to apply queueing theory in fitting a known parametric function to the distribution and to then sample directly from the estimate of the population. Clearly if a good fit could be obtained from the second option, then its use would be preferable to the first.

Statistical
~~Queueing~~ theory dictates that for a random stream of arrivals the probability of the arrival of another ship in a short time interval is proportional to the length of the interval, that is to say a Poisson distribution of arrival. From this it followed that the distribution of the inter-arrival times was represented by a negative exponential function, with a mean μ. It was found that only the route for vessels transitting the main-lane from the South Falls down to the Varne had enough observations, of the unscheduled traffic, to justify any form of statistical analysis. Of the minor unscheduled routes, such as the route for vessels from the Sunk area and down the routing scheme, the time was picked simply as a number from a random distribution.

Figure 7.1 shows the distribution of the observed inter-arrival times over a 48 hour period of time. For a total number of 169 vessels an arrival rate (λ) of:

169/2880 = 0.0587 vessels per minute was calculated.

Thus the mean inter-arrival time (μ) can be calculated as the reciprocal of the mean arrival rate:

1/0.0587 = 17.04 minutes between arrivals.

Assuming then a negative exponential distribution of the form

$$f(x) = \int_{x_1}^{x_2} \lambda e^{-\lambda x} dx$$

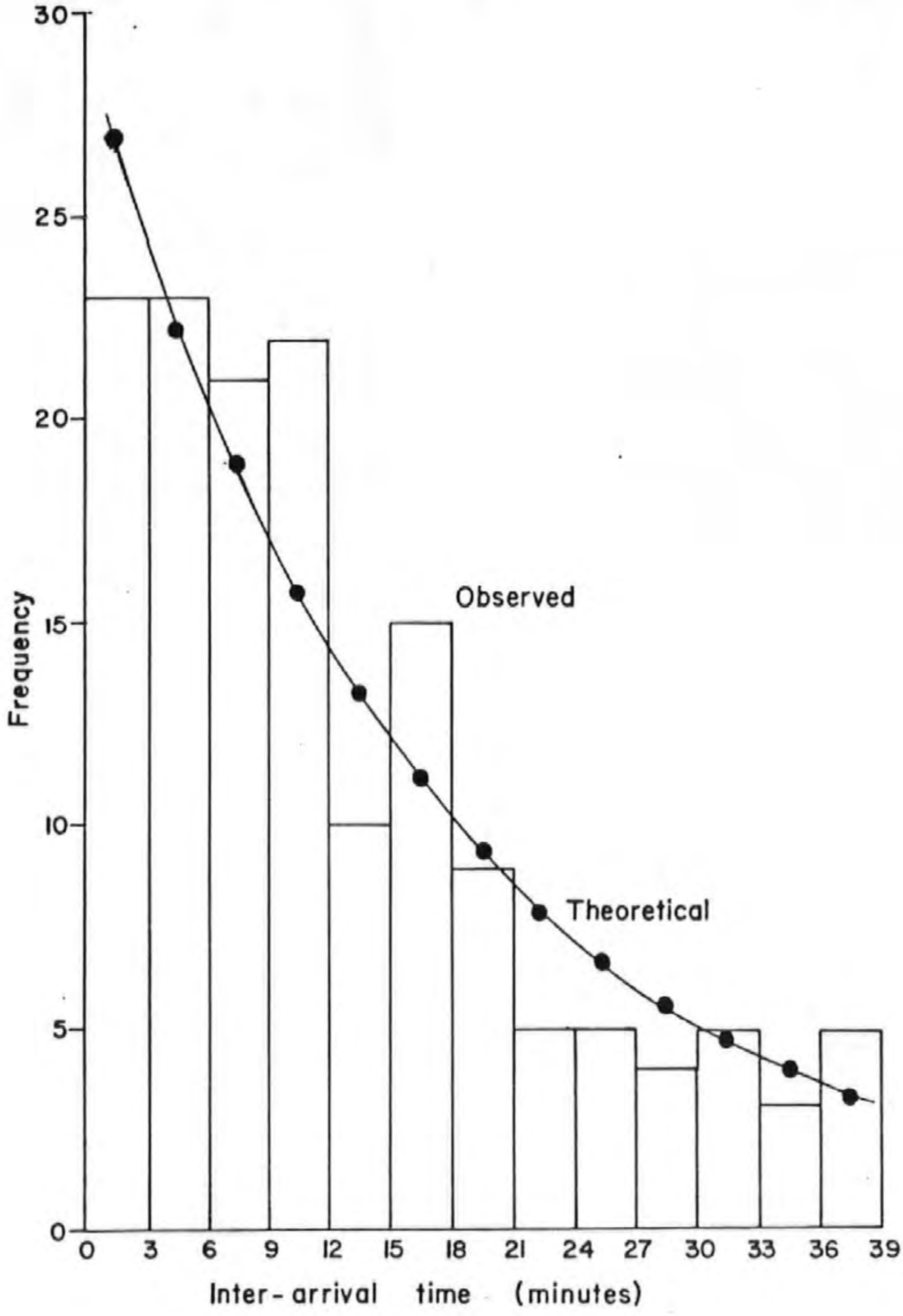


Fig. 7·1 Observed and theoretical distributions of Inter-arrival times for through vessels at the South Falls then the expected frequencies were determined as illustrated by the curved line in 7.1. The Chi-squared test was then used to validate the null hypothesis that the observed frequencies could be described by a negative exponential function. Consulting the Chi-squared tables, with 8 degrees of freedom, it was found that there was no reason to reject the null hypothesis at the 10% level of significance. As a result it was decided that the use of a negative exponential function with mean 17.04 would be used to generate a stream of traffic travelling down the main lane.

Distribution of ship types A further factor in a truely random sampling of ship traffic lay in the generation of ship types. It has been shown already that with the data available the only feasible means of categorizing vessels into their respective type classes was by the observed speed of the vessel. Figure 7.2 shows the observed distribution of ships' speeds for through traffic. It can be seen that the distribution is not symmetrical, with an emphasized sheer towards the lower speeds. This reflects the typical traffic pattern after omitting the fast ferries, with a large number of slower tramp and general cargo vessels and fewer fast vessels such as the containers. The mean speed of the distribution was 12.3 knots, with a standard deviation of 2.6 knots. It was decided once more, due to the lack of normality of the distribution to sample from the observed values.

Spatial distribution. It has been shown how the times of arrivals of vessels can be generated randomly to correspond to an initial

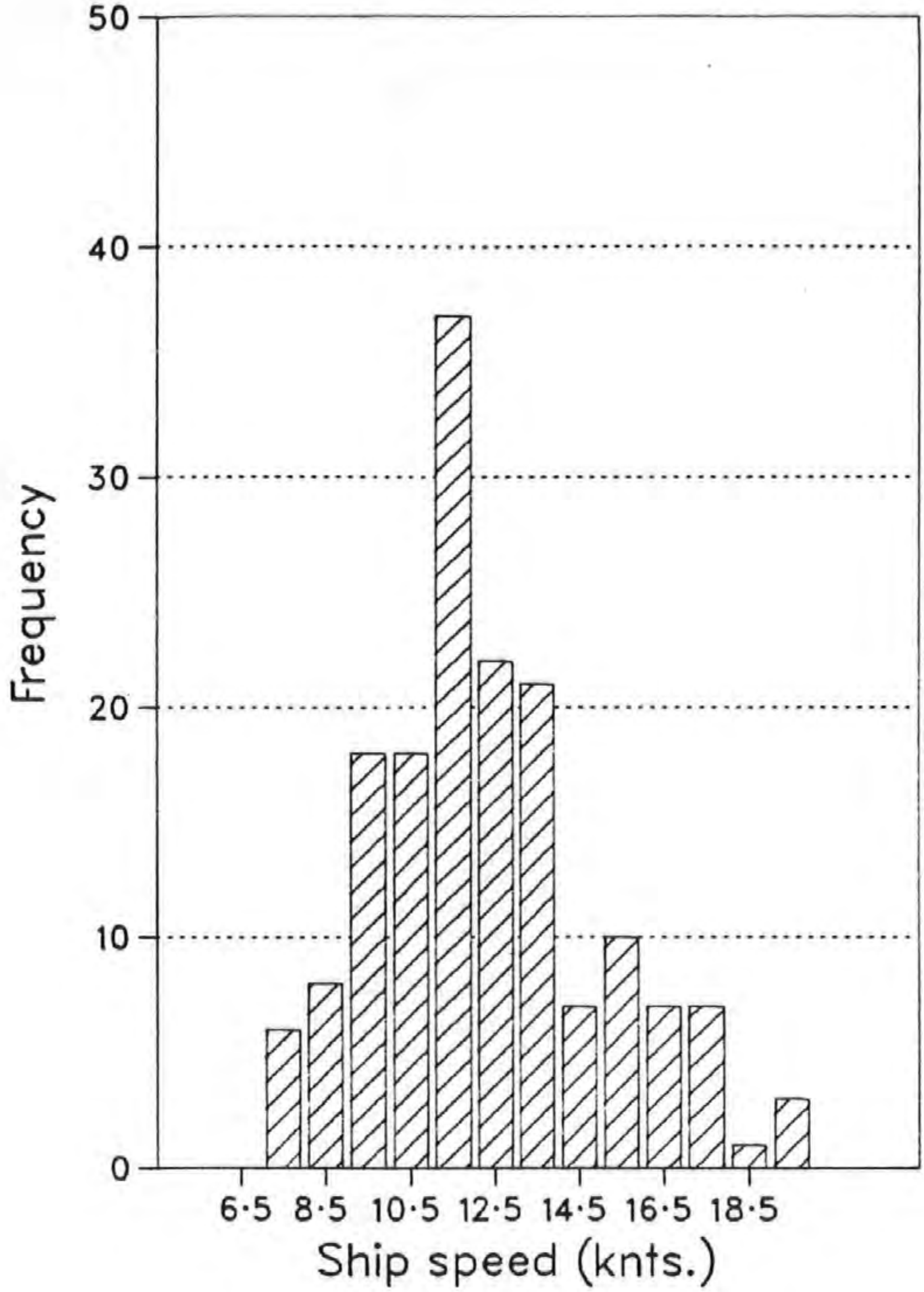


Fig. 7·2 Distribution of speeds of through traffic averaged over the length of the Main lane from the South Falls to the Varne statistical sample by comparing inter-arrival times at gates. The determination of a spatial distribution of vessels took much the same form. Again the survey of vessels for days 3 and 4 of the 24 mile radar film was used, with the direct access to starting positions enabling the calculation of accurate positions at gates. In this case there existed three main types of distribution:

a) the first when considering ferries leaving a port inside the simulation area in which case the starting position was unquestionably the grid co-ordinate of the harbour mouth;
b) the second when considering crossing traffic at the edge of the routing scheme;
c) and lastly the through vessels when entering the scheme at the South Falls.

It was observed from the track plots of vessels through the area that there were not enough ferries in each route to make any judgement concerning the distribution on entering the area. It was decided therefore to determine the limiting tracks for that route (this relates to the Degré concept of the beam) and to assume a uniform distribution within the beam. Figure 7.3 shows the observed distribution of through vessels at the South Falls. It can be seen that the spread resembles a skewed normal distribution, with the majority of vessels keeping close to the South Falls. It was concluded that the sampling of vessels without replacement would be the most satisfactory method of generating the vessels lateral displacement in the main-lane.

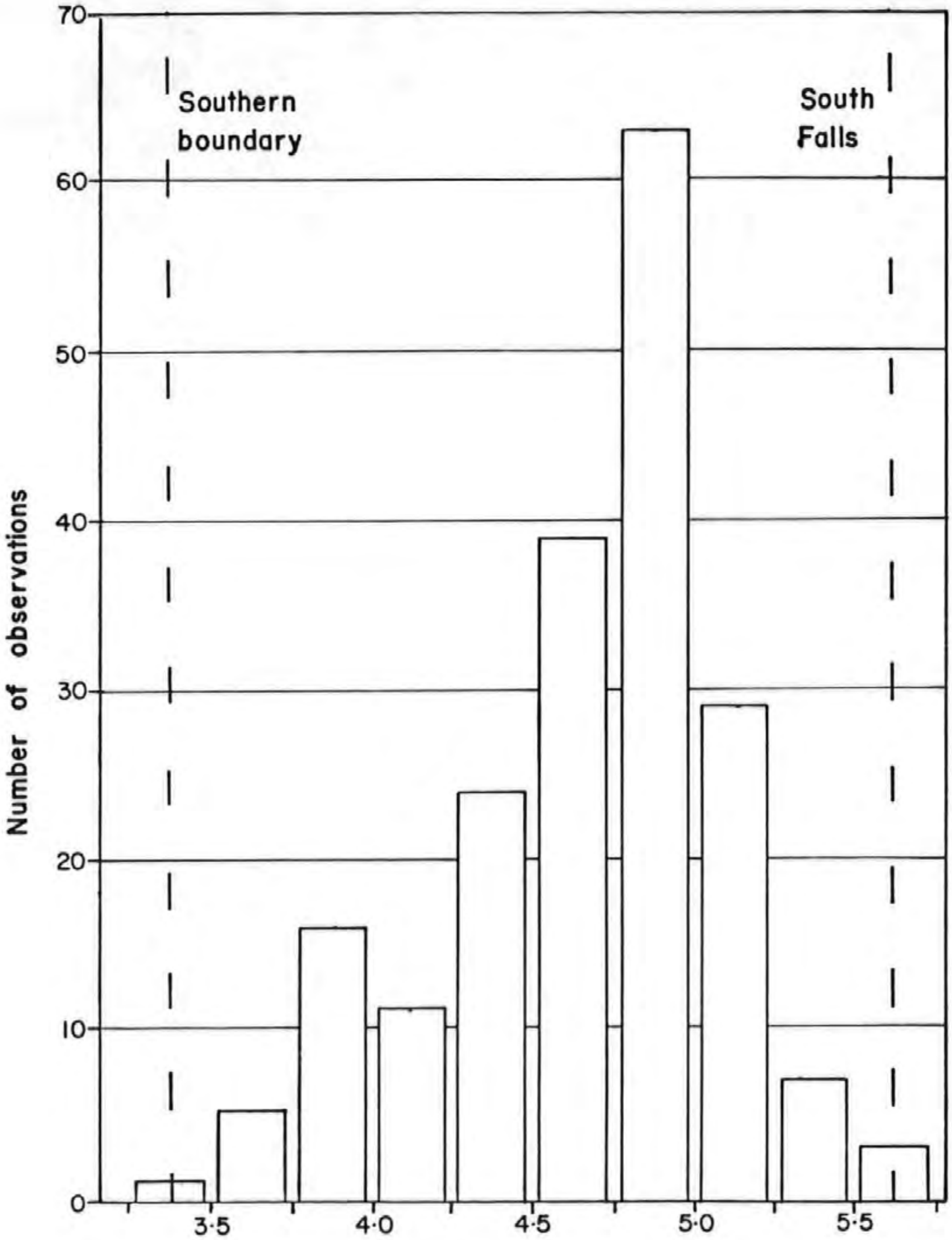


Fig. 7·3 Lateral distribution of through traffic at the South Falls

(x - axis is the y - ordinate on the grid)

The generation of random traffic. It was decided that rather than modifying the computer program so as to be able to incorporate the traffic generation algorithms a preferable method would be to devise a computer program to create the relevant data file. Thus the same set of random traffic could easily be utilized under varying conditions.

7.1.2 The design

It has been shown how the main program was constructed so that a variability in mariners' actions could be tested if necessary. It was decided however that for the validation process, the introduction of such a complication would have served no obvious purpose and as a result it was not included. Conversely the ability of ferries to alter course to cross at 90 degrees, and in so doing to cancel the requirement for a through vessel to take evasive action was permitted. This was less a complication to the stochastic process as a refinement to the collision avoidance logic, its existence being justified by the high frequency of such occurences in practice.

Although quite clearly the most valid form of comparison was that between the computer simulation run making direct use of the historical data in its setting-up procedure (Run 1), and the actual observed situation (Run 0), it was decided that a similar validation of the simulation run using randomly generated data (Run 2) would be useful. This was because the subsequent work on the simulation as a predictive aid required the use of the statistically generated data and consequently needed to be justified. Thus in all diagrams and explanations the three runs have been referred to solely as Run 1, Run 2 and Run 0.

7.1.2.1 An overview of validation procedures

It can be seen then that the validation consisted of comparing the results of Run 1 and Run 2 with Run 0. It was hoped initially to use the generated track plots for each run as one part of the validation, but the complexity of the diagram meant their use could only be as a rough, visual comparison of no real significance.

The majority of the validation tests involved a comparison between two non-parametric distributions, generally in the form of histograms. It seemed therefore valid to make use of the Chi-squared test. In the desire for brevity no attempt has been made to include all of the tables of figures, although in all relevant cases the value of the resulting test statistic, the number of degrees of freedom and the subsequent statistical validity of the null hypothesis have been included.

The main areas of validation involved comparisons of the Run 0 with the following sets of results from Runs 1 and 2:

a) the numbers and distributions of actual encounters;

b) the distributions of C.P.A.s;

c) the distribution of through traffic at the Varne;

d) the average lateral deviation due to collision avoidance and the average time spent manoeuvring for through traffic.

Encounters. The most obvious test involving encounters was a direct comparison between the numbers of each type of encounter. It was hoped initially to categorize the encounters as head-on, broad crossing, crossing, fine crossing, converging overtaking and parallel overtaking. It was decided however that the use of too many groups would have resulted in statistically insignificant sample sizes and as a consequence the more general categories of head-on, crossing and overtaking were used. These were determined both from the radar film and in the computer simulation by the geometric configuration and the relative velocities at the point of manoeuvre.

Although the number of encounters was a function of the system as a whole it was fundamentally a measure of the accuracy of the choice of domain sizes. This was because the main criterion in deciding whether an encounter was threatening or not, was the use of domain infringement. Therefore the choice of too small a domain for a particular type of encounter would quite clearly reduce the number of observed encounters for that type. A further influence on the number of encounters was the routes used by the vessels navigating through the area. It was decided therefore to analyse the effectiveness of the course array by considering the spatial distribution of the actual encounters across the grid. To do this analysis a program was developed to show a graphical representation of the frequencies. This graphical representation was known as the spatial distribution of frequencies, with frequencies at a particular grid element being represented by the number of tick marks. An example of this representation can be seen in Figure 7.5a.

In all cases sections of the grid were described as lanes, crossings or in the situation where a block was to be described as the bottom left hand corner and the top right hand corner of that block. Lanes run from bottom right to top left, whilst crossings run from bottom left to top right. The co-ordinate system used to describe blocks or in some cases, single elements is one of crossing followed by lane, thus the very top corner is (0,9).

<u>Closest points of approach.</u> The distribution of observed C.P.A.s was an indication of the effectiveness of the collision avoidance mechanism. An inspection of the number of close misses illustrated situations in which the model found itself in difficulties. Values of C.P.A.s around and slightly greater than the relevant domain size reflected the magnitude and duration of the collision avoidance manoeuvres. The larger values of C.P.A.s, 1 n.mile and over,were indicative of the distance between neighbouring routes and hence a measure of the control of the course array.

Again, in a similar fashion to the comparison of encounters, a spatial distribution of C.P.A.s less than a particular threshold value ~~were~~ was considered. The C.P.A.s chosen were those less than or equal to 1 n.mile and those less than or equal to 6 cables. Six cables was chosen because it was the largest domain size and consequently it represented the distribution of relatively close approaches. The value of 1 n.mile was chosen after consulting Table 3.1, from which it was found that it represented the C.P.A. at which no mariners felt threatened and was consequently a measure of the system structure as opposed to the encounter structure.

Distribution at Varne. The four sets of tests so far have all considered essentially the ability and the accuracy of the simulation in detecting and analysing threatening situations and in executing any subsequent collision avoidance manoeuvres. The analysis of the distribution of through vessels at the Varne allowed the assessment of three main model functions: the combined collision avoidance action by through traffic; the means by which vessels navigated through the T.S.S. and on being forced to manoeuvre into the E.I.T.Z. the manner in which they returned to the main lane; and finally the process by which vessels alter course to avoid the Varne. This analysis involved counting the numbers of vessels through gates set either side of the Varne. They were sited to run perpendicular to the main lane and were divided into 1/4 mile sections, with gates 0 and -1 on either side of the Varne, with increasing values to the north-west and decreasing values to the south-east. In all cases the gates through which the vessels passed were described by the gate number.

The average lateral deviation and duration of manoeuvres. This penultimate test in the validation procedure was introduced as a means of comparing the magnitudes and durations of manoeuvres for through traffic. The average lateral deviation was determined from the sum of the absolute values of all manoeuvres by through vessels off their desired courses and the total number of observed manoeuvres by such vessels. The average deviation was determined in the same manner except in this case the total time from the start of the manoeuvre to the final alter back on to course was determined.

The qualitative assessment of ship's tracks. Clearly the ideal form of validation would have been that utilized by Davis when a direct comparison was made of ship's tracks generated by the model with those observed from the radar film. In this situation however there would have been little likelihood of reproducing exactly the same initial starting positions immediately before the encounter to be used for validation. There would then have been nothing to be gained in attempting to compare simulated and observed encounters directly. A series of encounters from an eight hour run have been extracted and and descriptions given of the main occurrences.

7.2 Results

7.2.1 Encounter distributions

7.2.1.1 A comparison of the numbers of encounters

Figure 7.4 shows the distribution of the frequency of encounters for Runs 1,2 and 0 in total and sub-divided into the type of encounter at the point of manoeuvre. The following broad observations were made:

a) both simulated runs (Runs 1 and 2) recorded more encounters in total than the observed results (Run 0);

b) the difference in the total number of encounters was almost all accounted for in the low number of observed overtaking encounters. This was almost certainly because of the difficulty found in determining whether or not a manoeuvre to overtake another vessel had taken place in the radar film analysis;

c) the numbers of crossing encounters were insignificantly different for all three runs;

d) the small numbers of head-on encounters for all three runs reduced the statistical significance of any conclusions that might have been drawn from their results.

The quantitative assessment compared the frequencies shown for each run, excluding the total values which would have resulted in a duplication. The Null hypothesis to be assumed for all the tests making use of the Chi-squared test was that both distributions being compared were from the same population. Clearly the values normally referred to as the observed values in the Chi-squared test are simulated values whilst those normally referred to as the expected are the observed value (Run 0).

A comparison between Run 1 and Run 0 gave a test statistic of 31.4. For 3 degrees of freedom there is no reason to accept the Null hypothesis at the 5% level.

A comparison between Run 2 and Run 0 gave a test statistic of 11.2. The null hypothesis is significant at the 1% level.

It can be seen that in both cases the comparison does not give very good results. This is due almost entirely to the difficulty in assessing the number of observed overtaking encounters.

On omitting the overtaking encounters test statistics of 1.5 and 7.8 were obtained for Run 1 and Run 2 respectively. For two degrees of freedom this meant that the null hypothesis was significant for Run 1 at the 10% level whilst that for Run 2 was significant at the 2% level.

7.2.1.2 A comparison of the spatial distributions of encounters

Figures 7.5, 7.6 and 7.7 show the spatial distributions of runs 1, 2 and 0 respectively and are, in each case sub-divided into sections a, b, c and d relating to the total, head-on, crossing and overtaking encounters respectively.

The following points can be observed from Figures 7.5a, 7.6a and 7.7a:

a) in all three cases the main density of shipping (represented by high frequencies) was concentrated down lanes 4 and 5;

b) the fan of ferry traffic to and from Dover could be identified from the spread of higher frequency observations from Dover, grid section (4,8).

On consideration of the head-on encounters (Figs. 7.5b, 7.6b and 7.7b) little could be deduced due to the small numbers of observations. It could be seen that there was an increased density in the region (2,5), (8,8) which corresponded again to the ferries to and from Dover.

The comparison of the crossing encounters was interesting with Run 2 and Run 0 both indicating that no crossing encounters took place in lanes 0,1 or 2, whilst Run 1 recorded only two encounters in the same region. Run 2 demonstrated a peaking in the element (11,3), whilst Run 0 peaked in the neighbouring elements (10,5) and (11,5). It could also be seen in all three runs that there was an element in the middle of the fan of traffic leaving Dover, at (5,6) that recorded no encounters. This was indicative of the divergence in the route from

Dover to Calais from the route from Dover to Dunkerque.

Finally a comparison can be made of the overtaking encounters. It can be seen that in all three cases the density of remained relatively constant along the length of the routing scheme, with the greatest density in lane 5.

Fig.7.4 Distribution of encounters

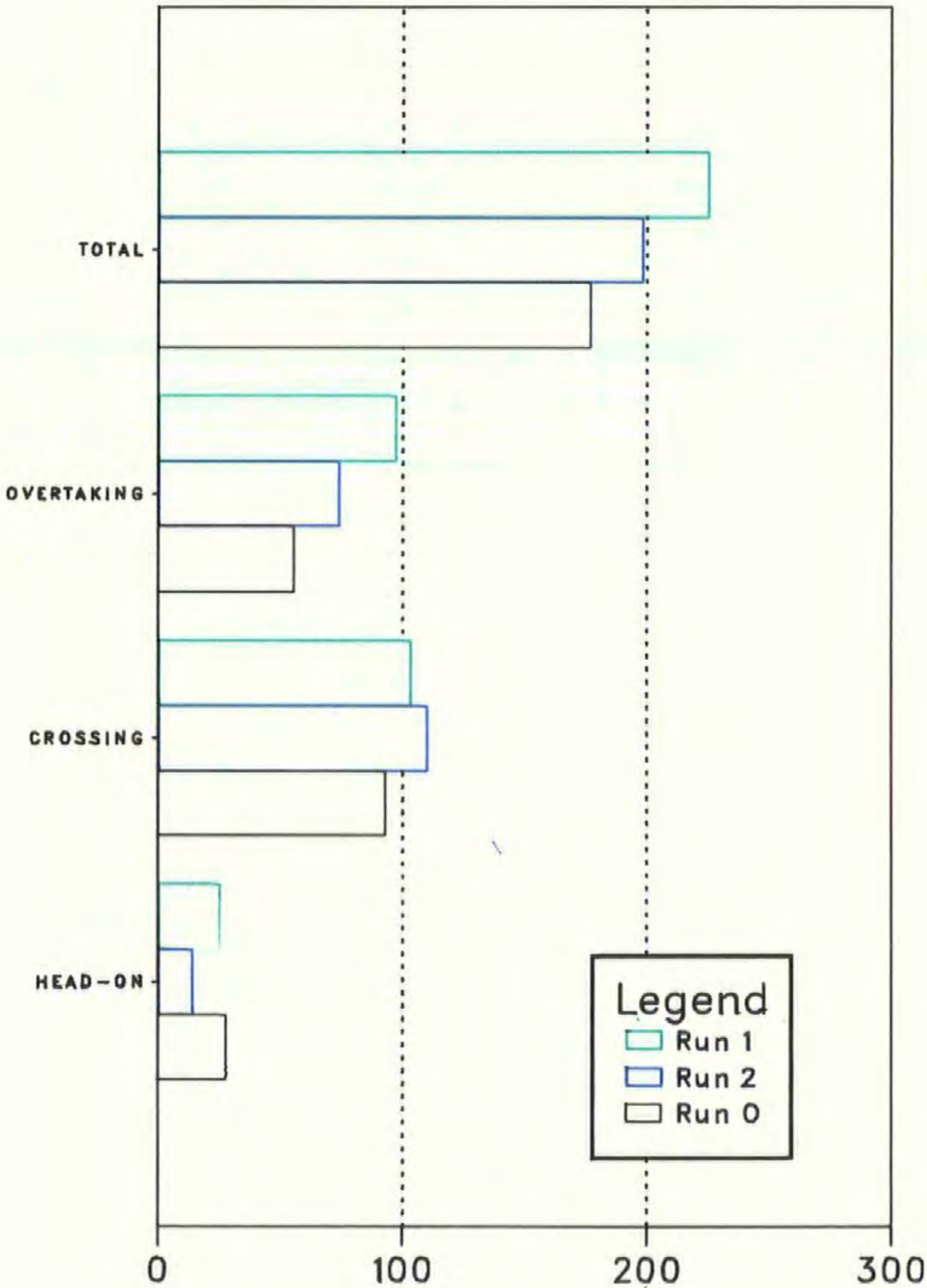


Fig.7.5a Run 1 – All encounters

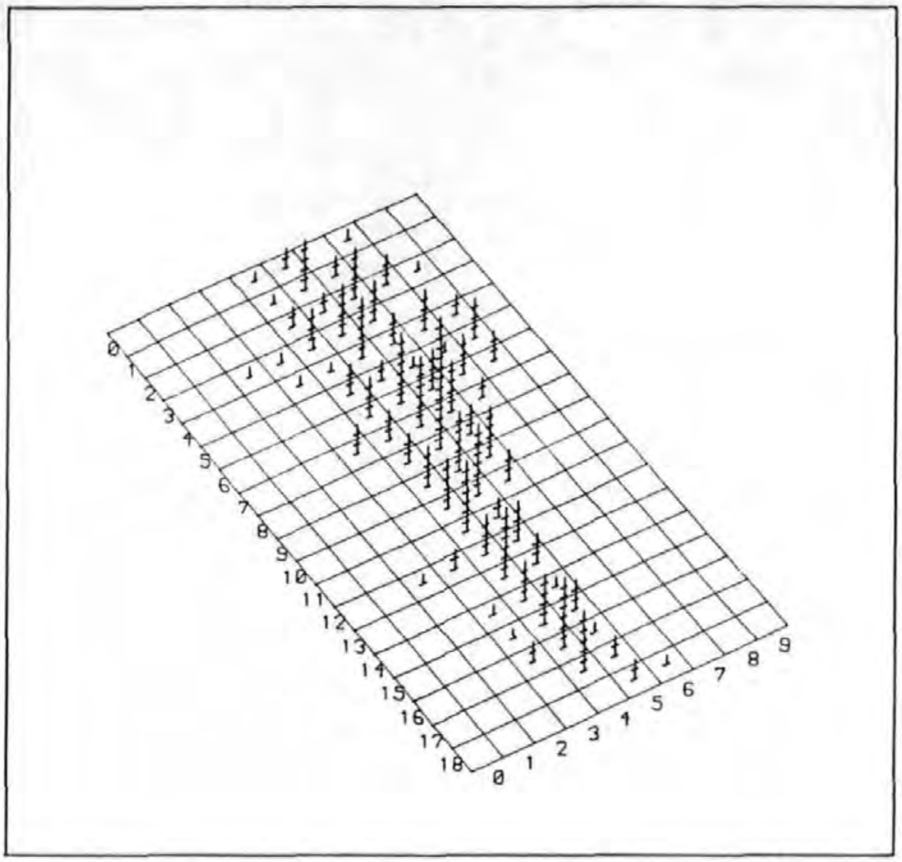


Fig.7.5b Run 1 – Head-on encounters

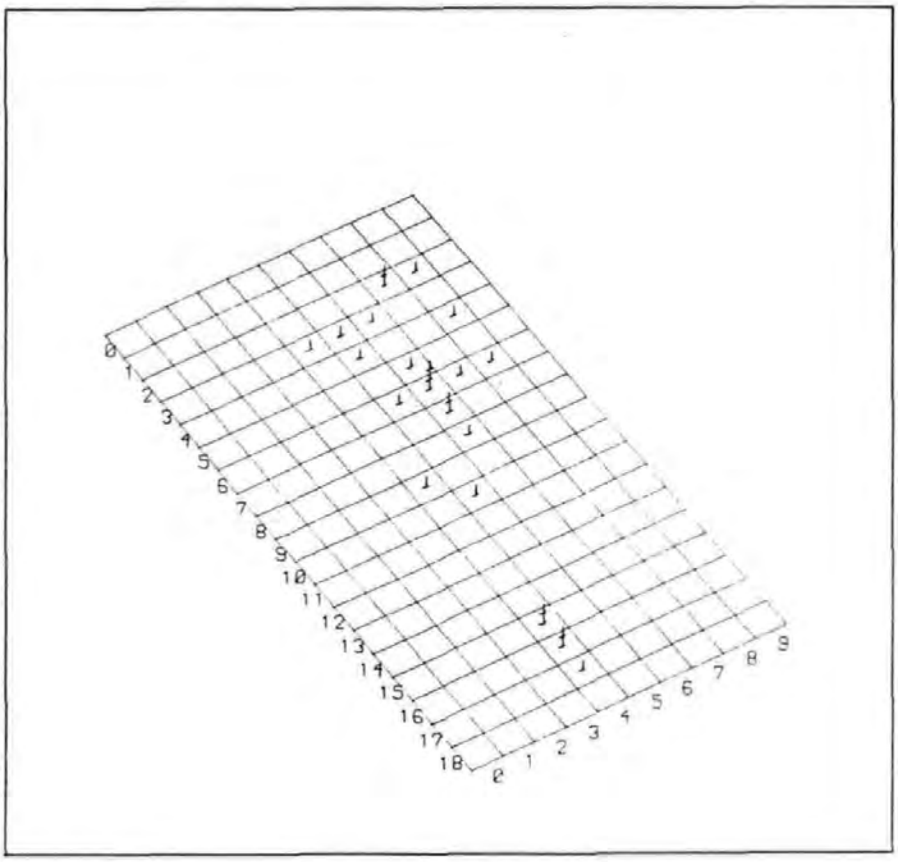


Fig.7.5c Run 1 – Crossing encounters

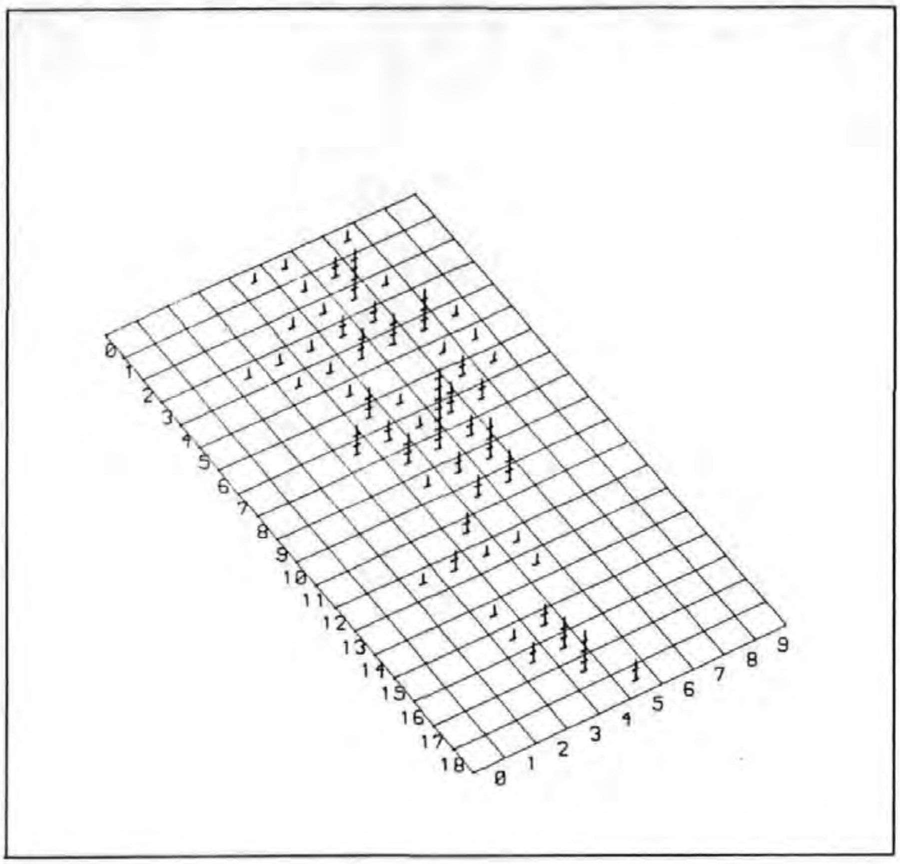


Fig.7.5d Run 1 – Overtaking encounters

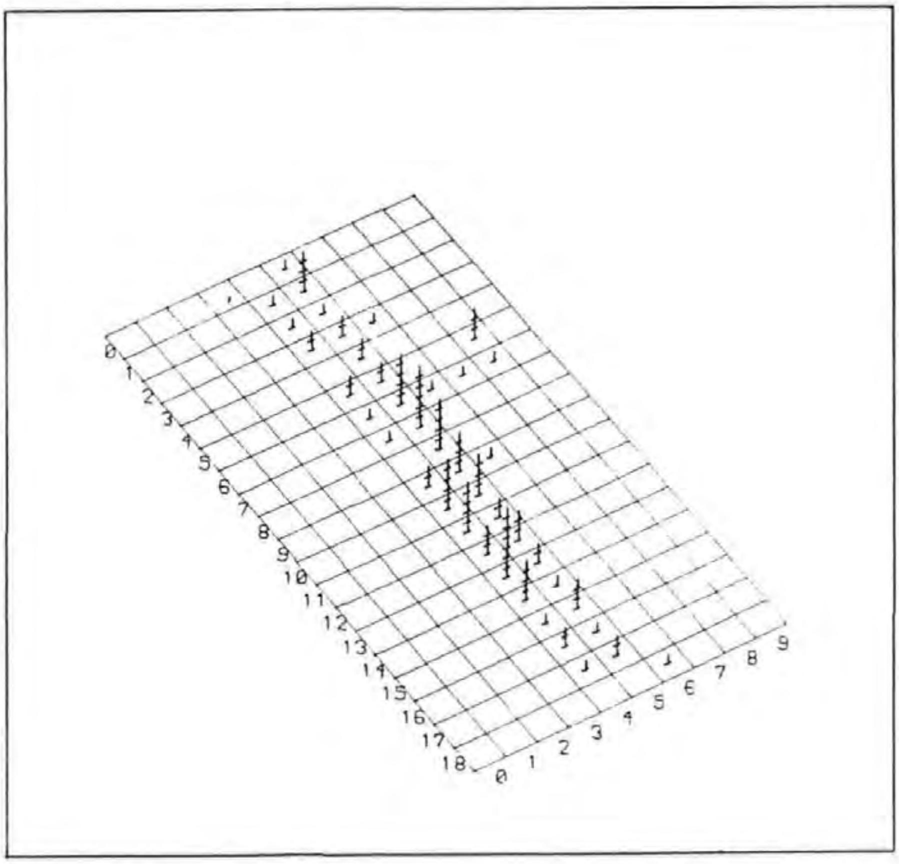


Fig.7.6a Run 2 – All encounters

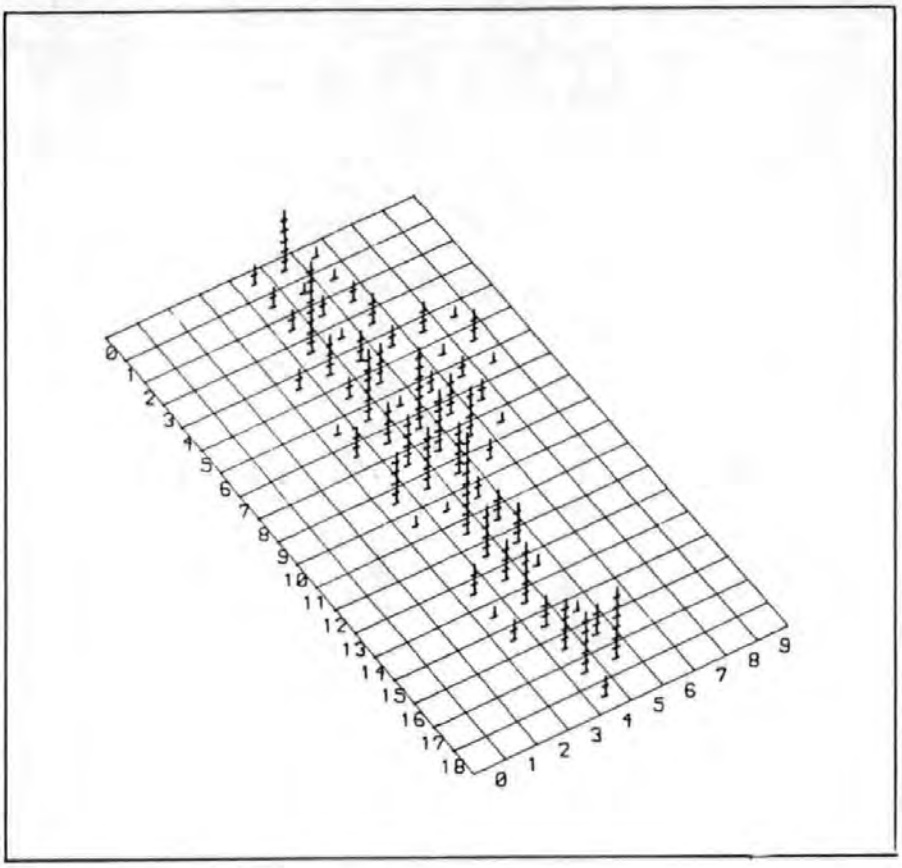


Fig.7.6b Run 2 – Head-on encounters

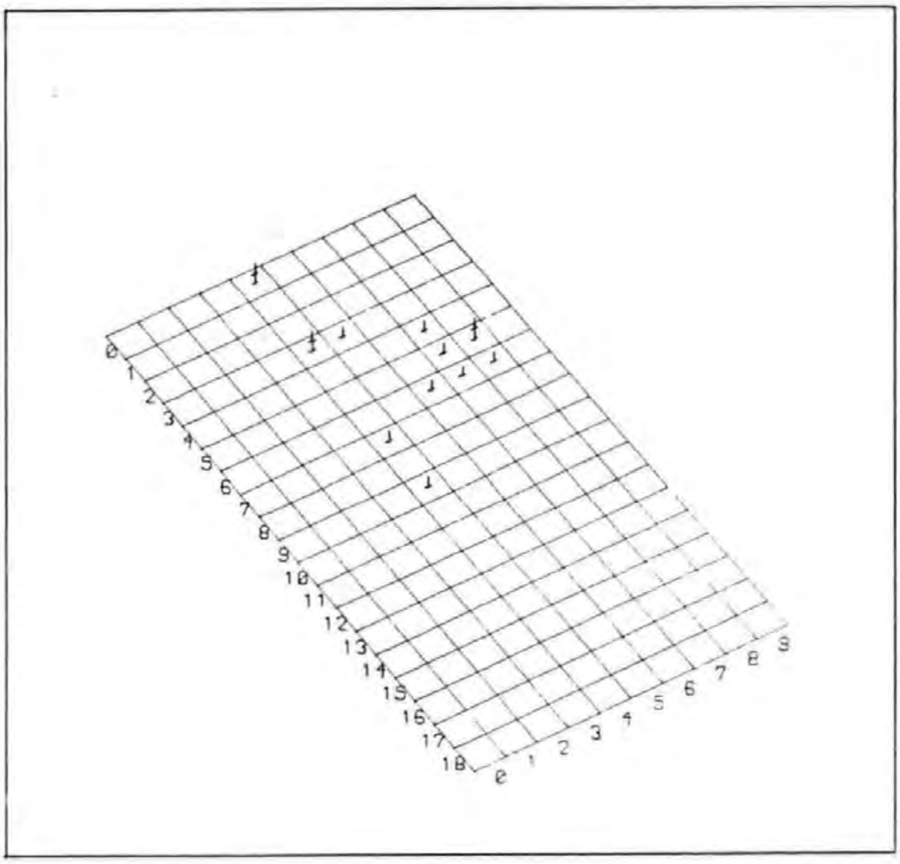


Fig.7.6c Run 2 – Crossing encounters

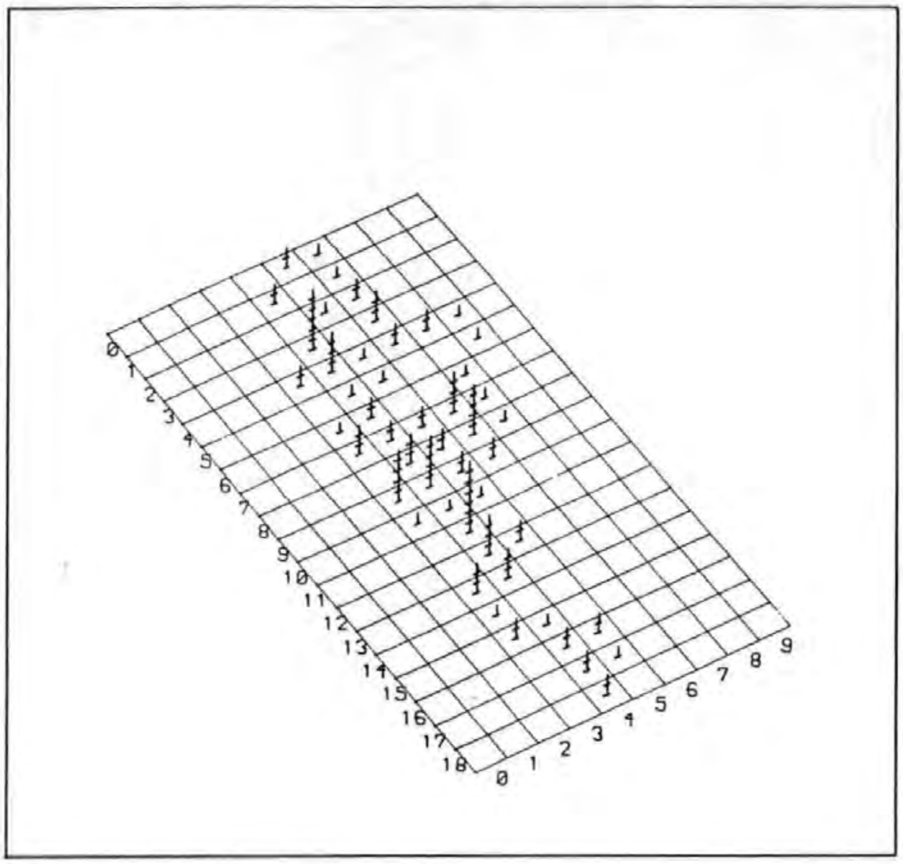


Fig.7.6d Run 2 – Overtaking encounters

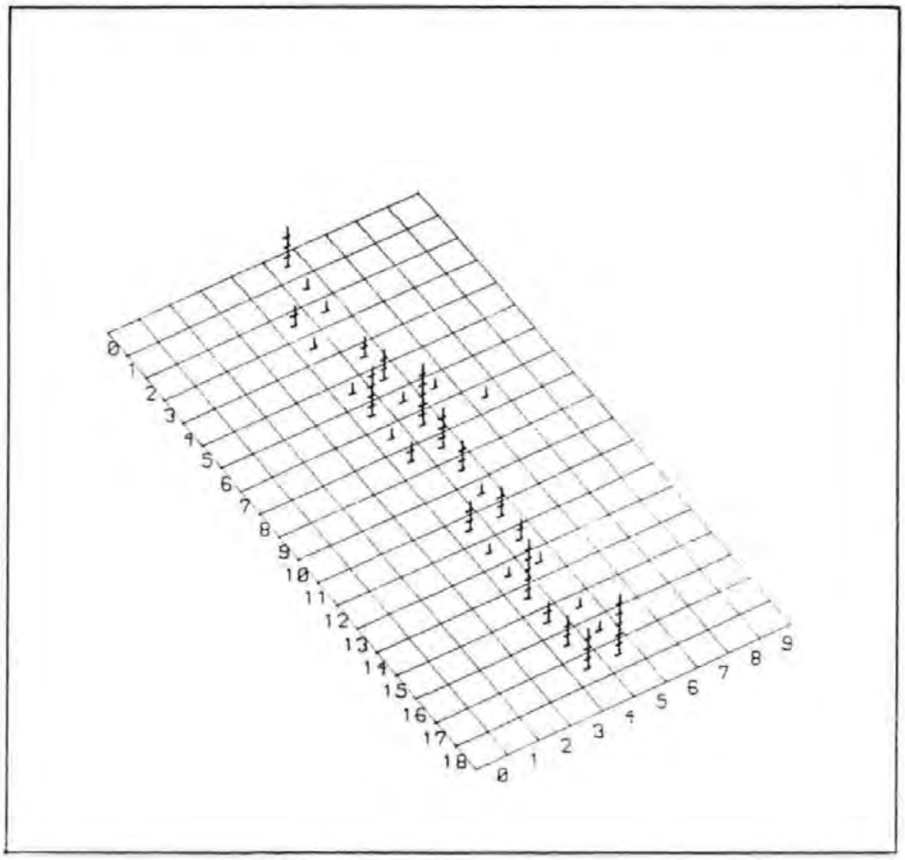


Fig.7.7a Run 0 - All encounters

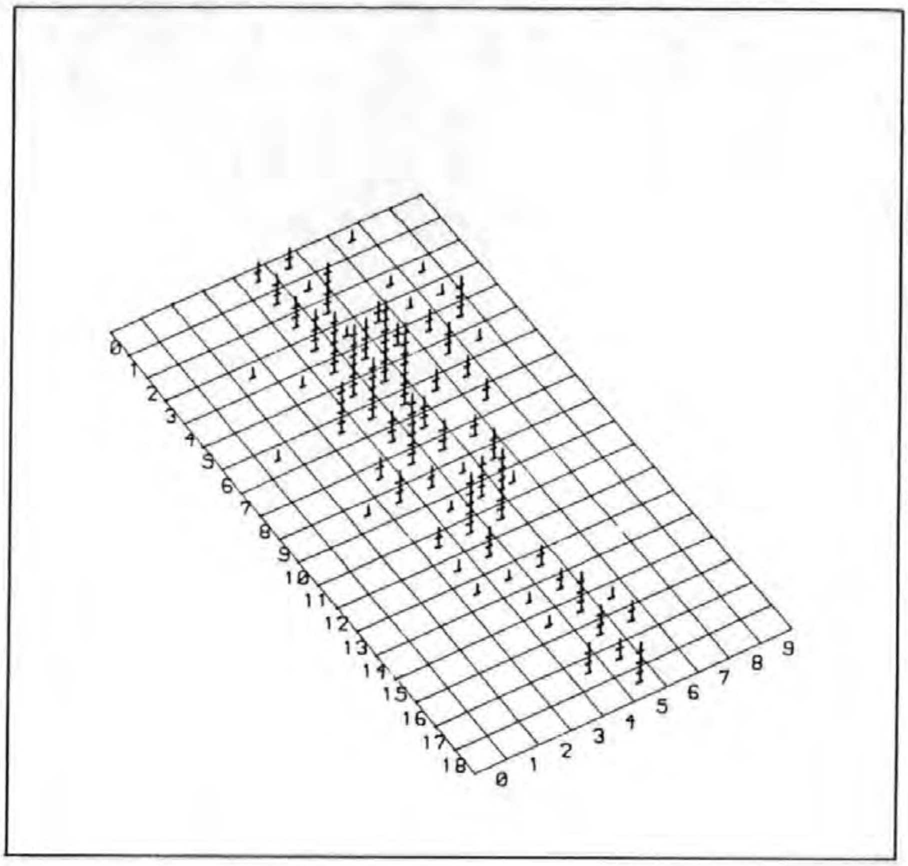


Fig.7.7b Run 0 - Head-on encounters

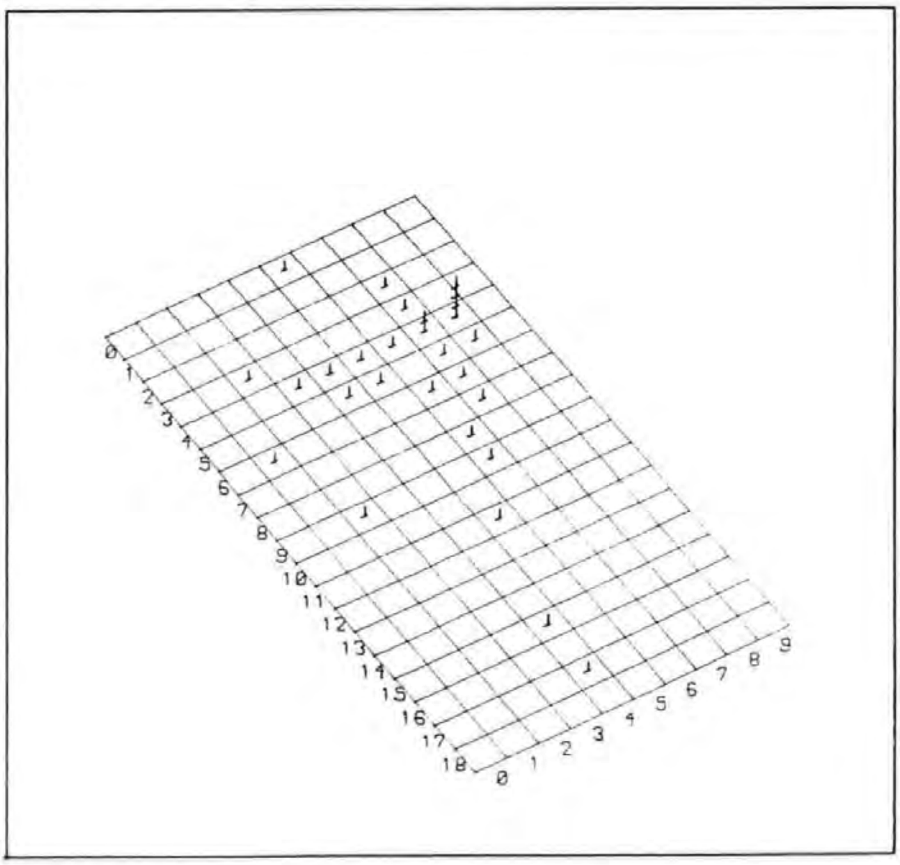


Fig.7.7c Run 0 – Crossing encounters

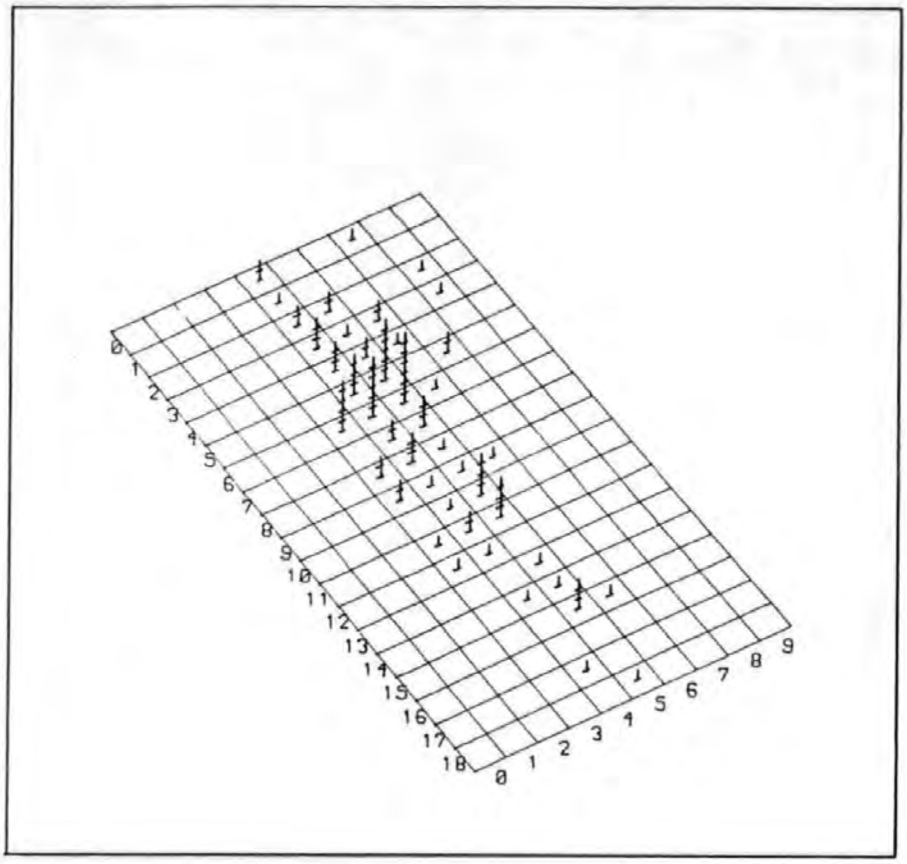
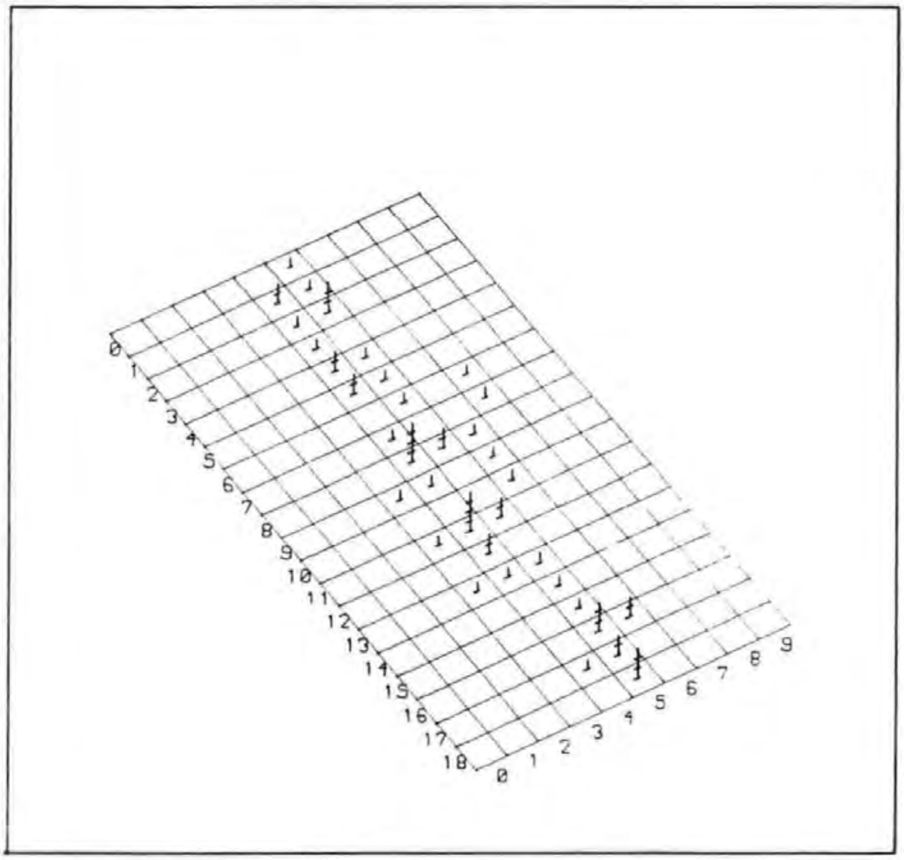


Fig.7.7d Run 0 – Overtaking encounters



7.2.2 Analysis of Closest Points of Approach

7.2.2.1 A comparison of the distribution of C.P.A.s

Figure 7.8 shows the distribution of C.P.A.s for the head-on situations. It can be seen that there were no observed values greater than 1 n.mile. This was because it was found to be too difficult to attempt to observe C.P.A.s over that value. For this reason although the frequencies for C.P.A.s of 1 n.mile up to 2 n.mile are shown also on the simulation run distributions they have not been included in any statistical comparison.

Figure 7.9 illustrates the distributions of C.P.A.s for the head-on situations. It can be seen that Run 2 produced far less head-on situations than either Run 1 or Run 0. It was thought that this was probably due to the manner in which vessels positions were set up on the southern grid boundary. This was done by noting the limits of the starting positions for each crossing route and then randomly choosing a position within the specified range assuming a uniform distribution. In retrospect it was thought that the lateral positioning was not a random process but was due to changes in the tidal stream and hence varied with time. The result of this speculation would have been that in practice vessels crossed in narrower paths than in the model, resulting in a greater number of head-on situations.

Figure 7.10 shows the distribution of C.P.A.s for crossing situations. It indicates a good agreement between the simulated and observed runs in both cases, in particular for the C.P.A.s between 0 and 6 cables.

Figure 7.11 shows the distribution of C.P.A.s for overtaking encounters. Again a good agreement is displayed between observed and simulated for both runs 1 and 2.

In general it would appear that the best agreement was in the range 0 to 6 cables. It was thought the reason for the loss of agreement after this point was due essentially to the ease with which the greater C.P.A.s could be missed.

7.2.2.2 A comparison of the spatial distributions of C.P.A.s

The spatial distributions of all C.P.A.s less than or equal to 1.0 n.miles are shown in Figures 7.12a, 7.13a and 7.14a for runs 1, 2 and 0 respectively. The diagrams illustrate more fully than the encounter diagrams how the main routes run and intersect. The heavy density of shipping can clearly be seen travelling down lanes 4 and 5 again with a relatively uniform density along their length. The broad fan of vessels leaving and entering Dover can be seen quite clearly. The two simulation runs both have peaks at the Varne and in the vicinity of the Dover Harbour mouth. The former was due to the navigation of vessels away from the marker buoy whilst the latter was due to the lack of scheduling in the ferry operations.

Figures 7.12b, 7.13b and 7.14b show the same runs only in this situation for C.P.A.s less than or equal to 0.6 n.miles. It can be seen that there is little change in the shape of the distributions although there is as would be expected a significant reduction in the frequencies.

In general then there is a greater spread of frequencies across the grid in the observed than in the simulated runs. This is due partly to the natural rationalization process adopted in determining the most frequently used routes and partly because of the great variability in mariners actions that could not be totally reproduced in the model.

Fig.7.8 Distribution of C.P.A.s for all encounters

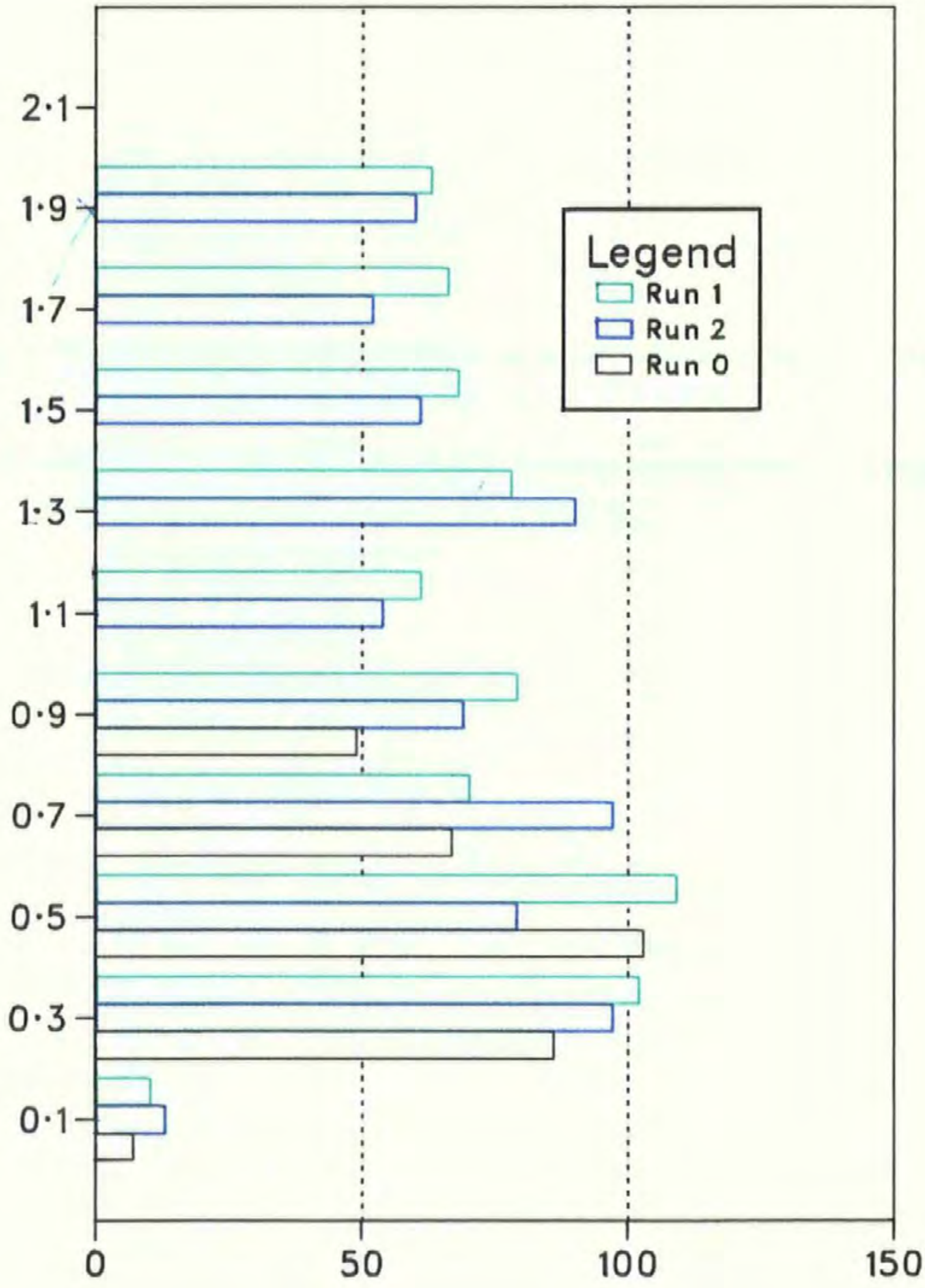


Fig.7.9 Distribution of C.P.A.s for head—on encounters

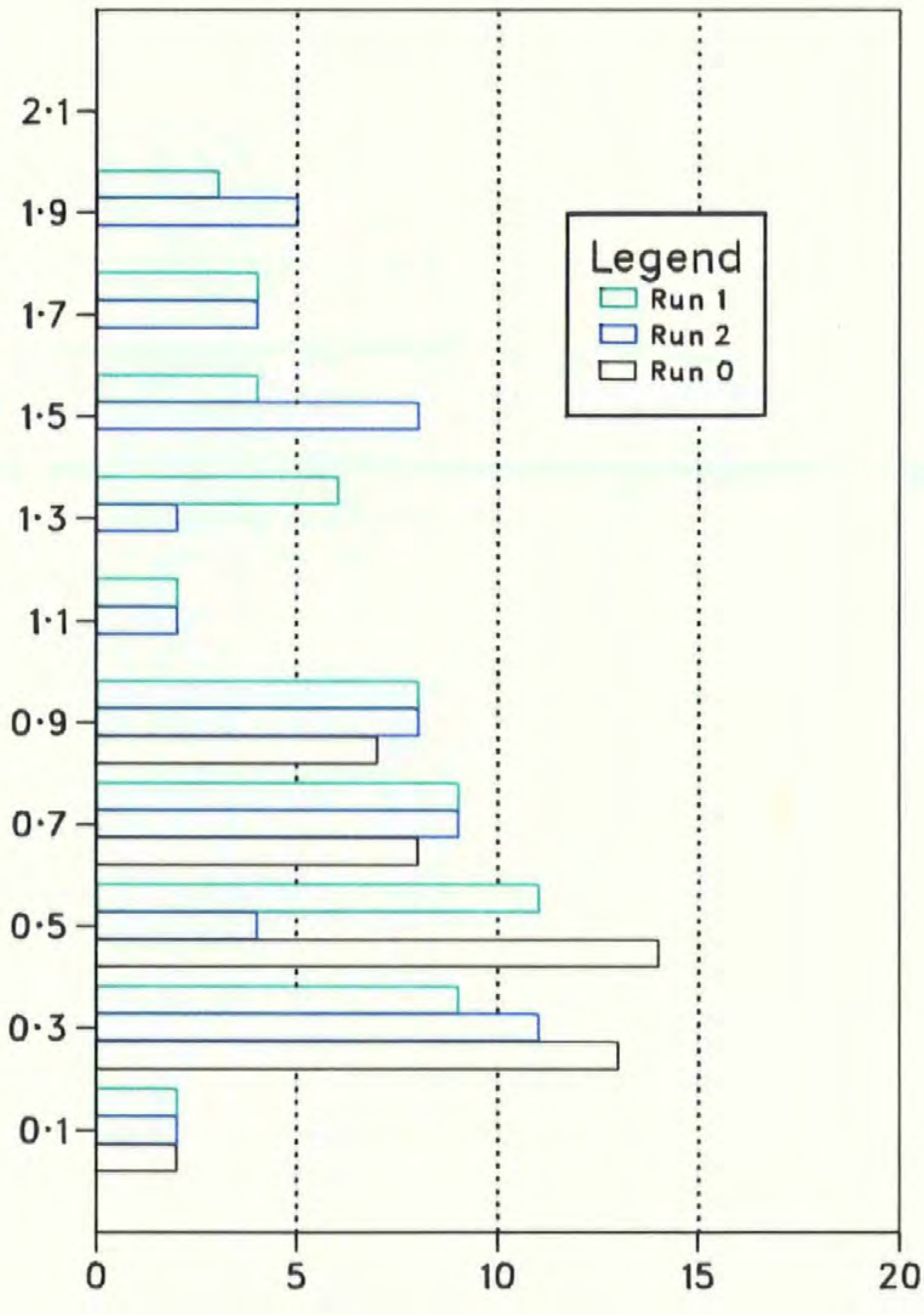


Fig.7.10 Distribution of C.P.A.s for crossing encounters

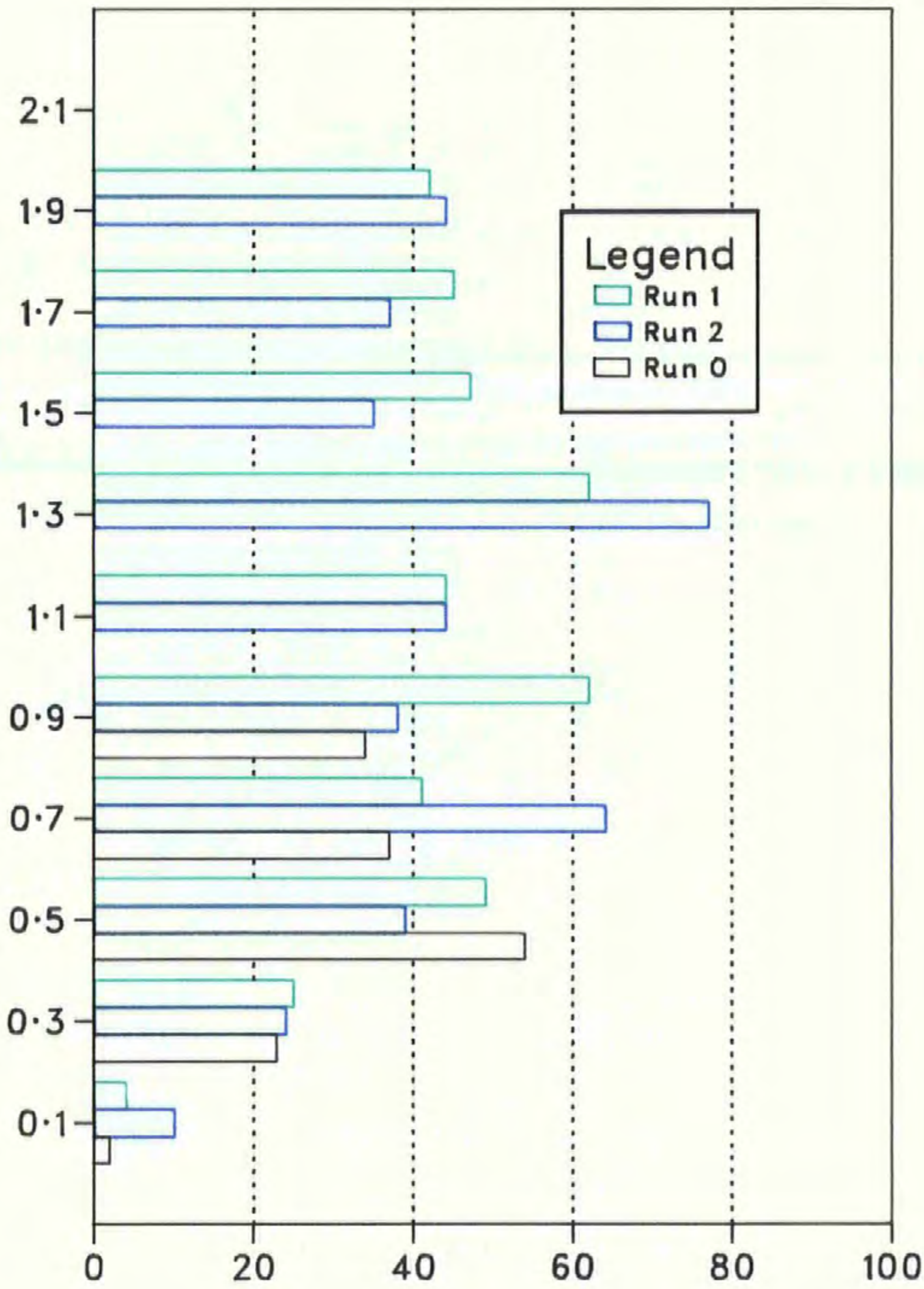


Fig.7.11 Distribution of C.P.A.s for overtaking encounters

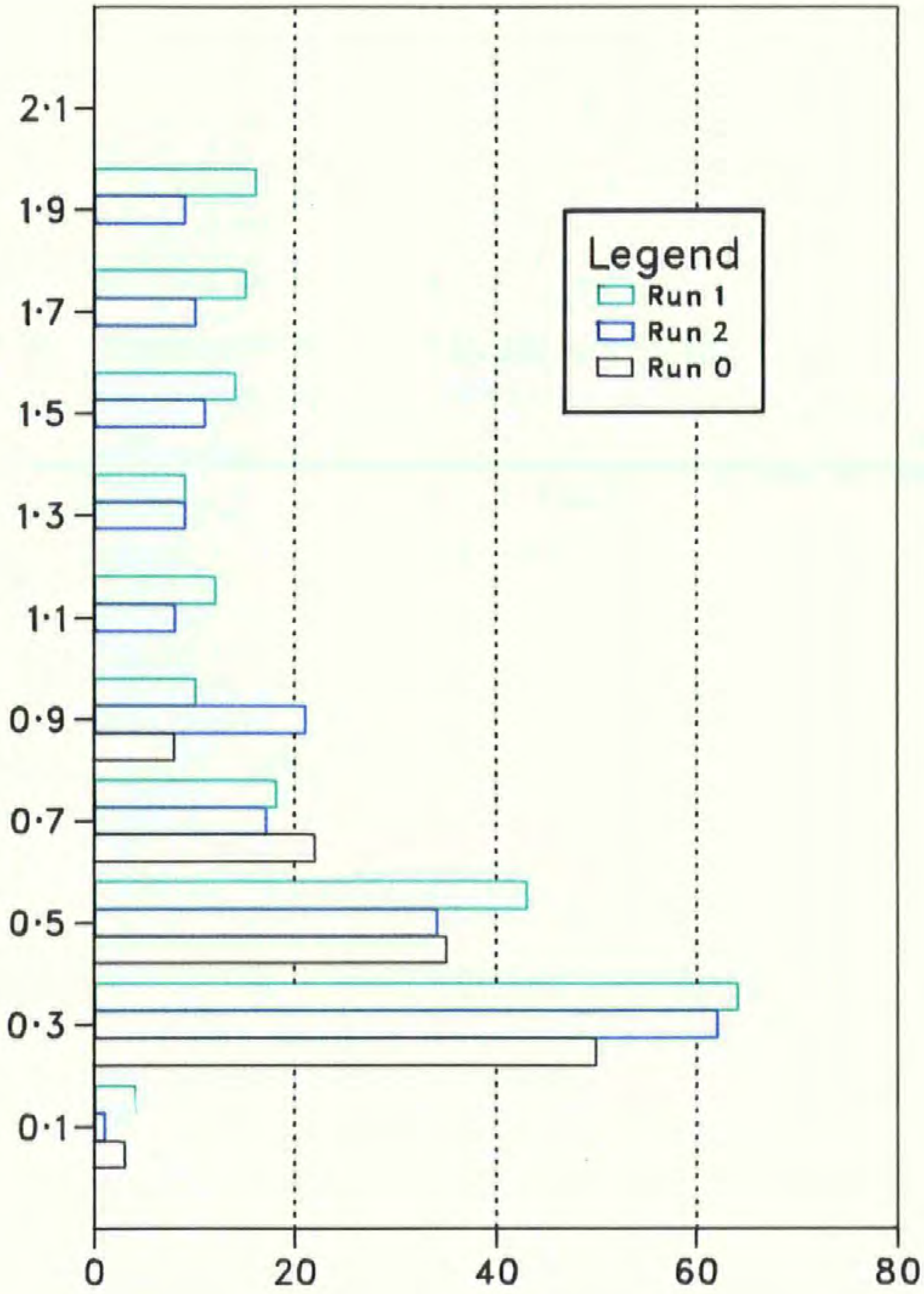


Fig.7.12a **Run 1 – C.P.A.s <= 1.0**

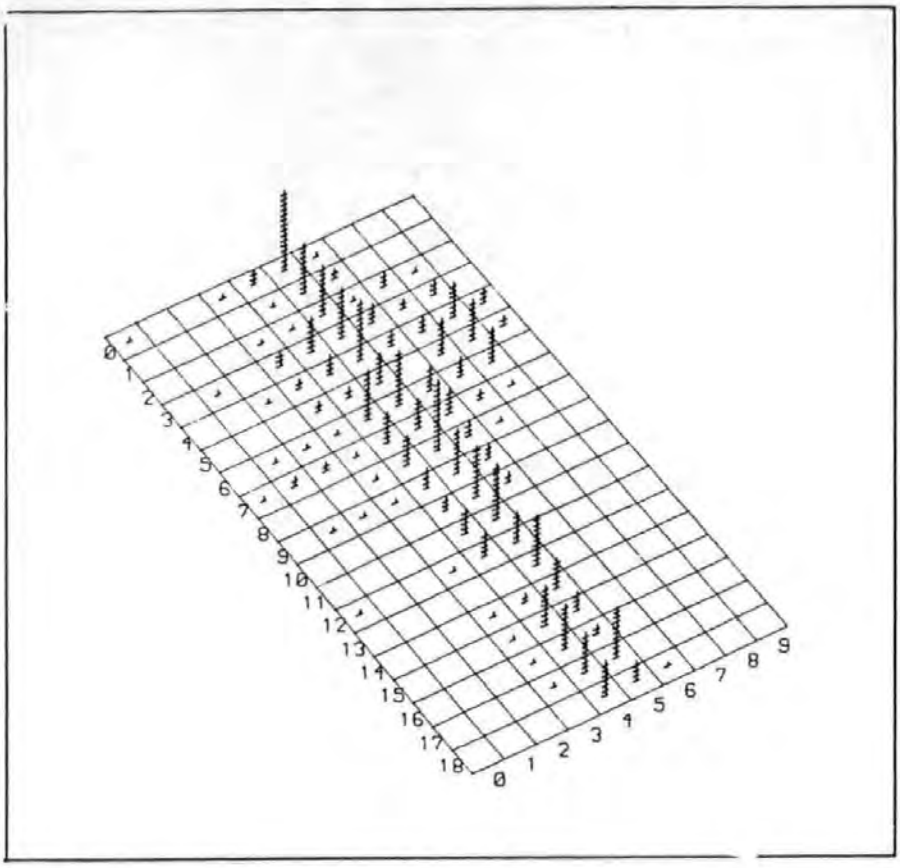


Fig.7.12b **Run 1 – C.P.A.s <= 0.6**

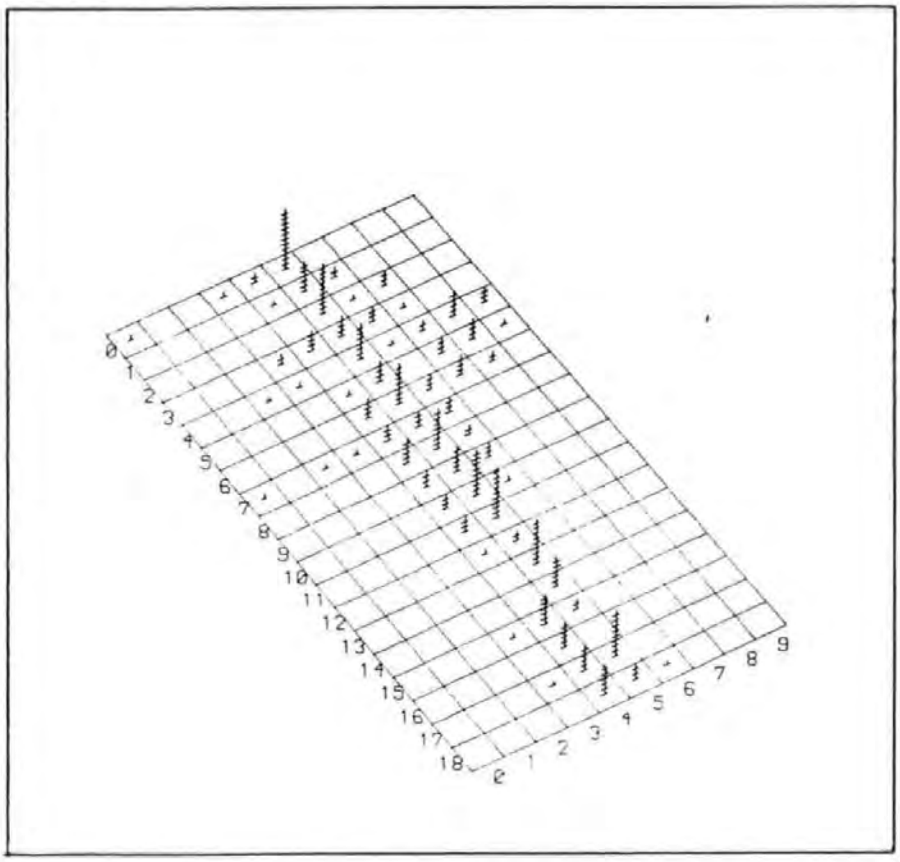


Fig.7.13a Run 2 – C.P.A.s <= 1.0

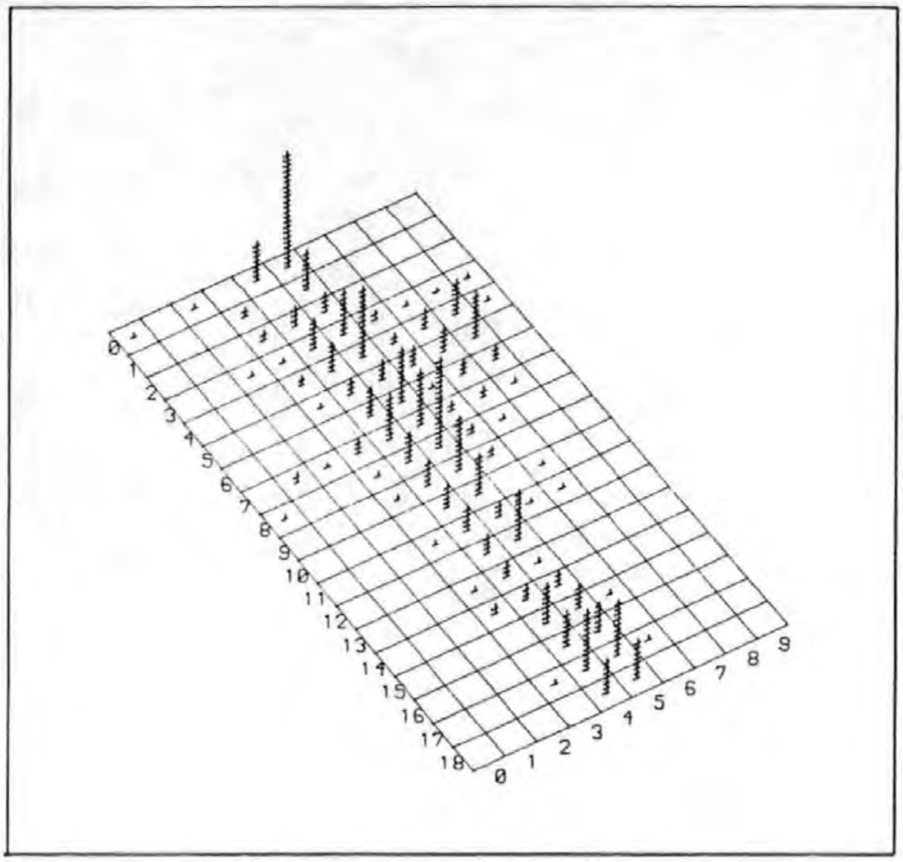


Fig.7.13b Run 2 – C.P.A.s <= 0.6

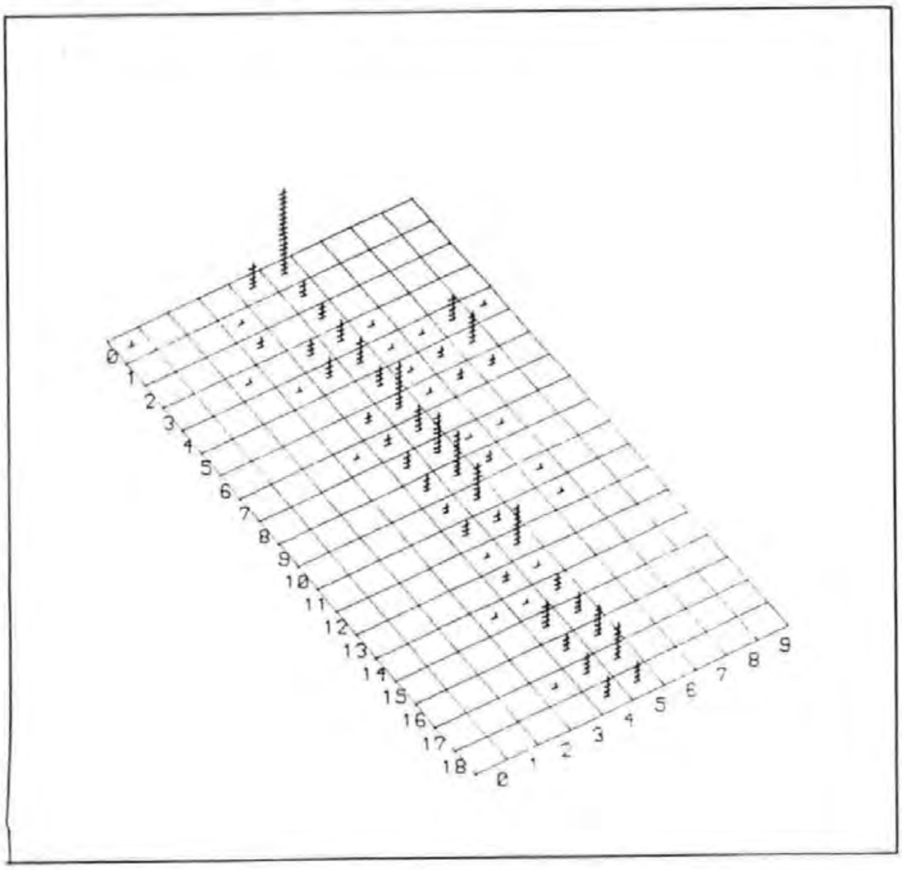


Fig.7.14a Run 0 - C.P.A.s <= 1.0

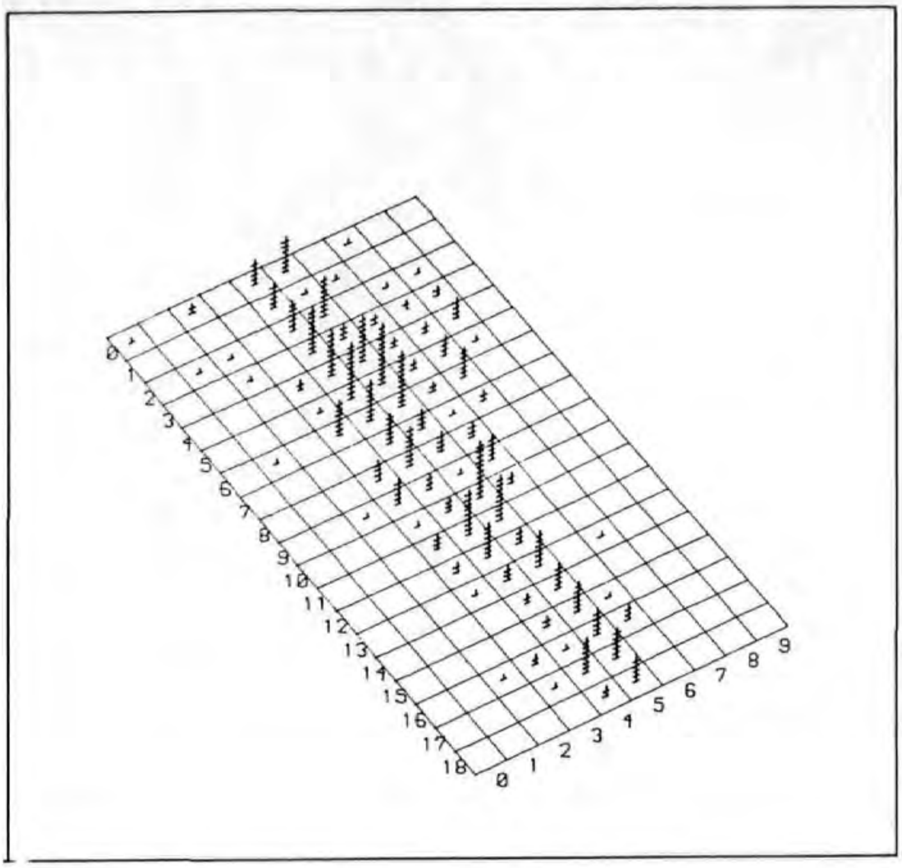
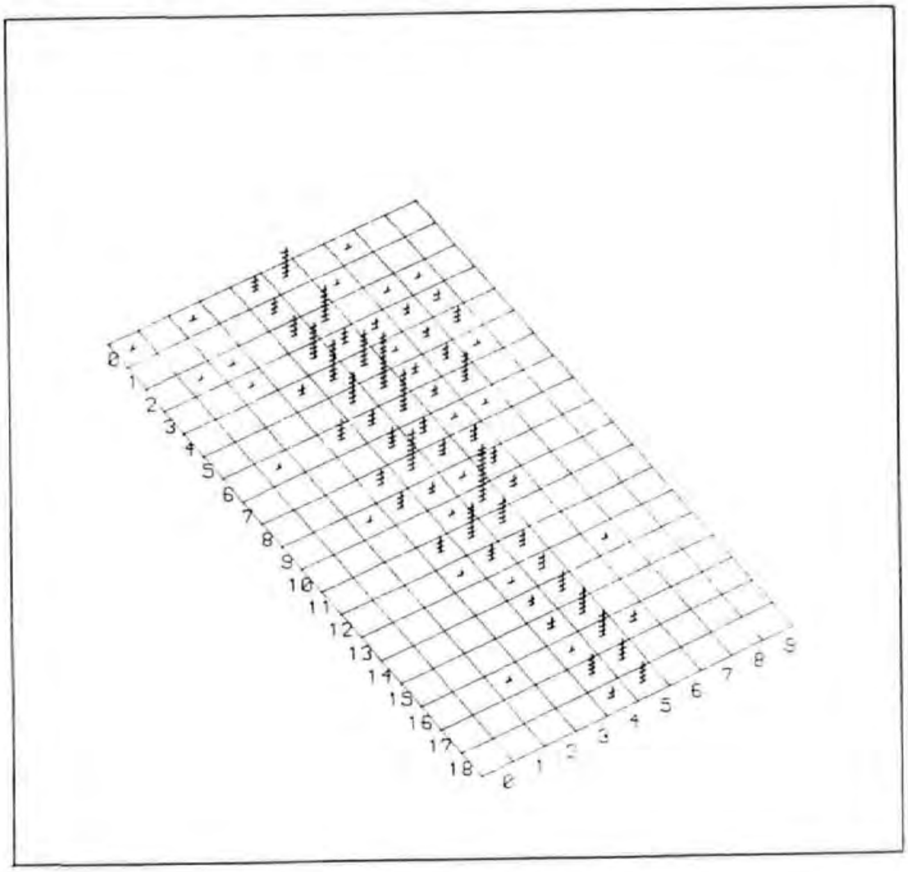


Fig.7.14b Run 0 - C.P.A.s <= 0.6



7.2.3 The distribution of through traffic at Varne

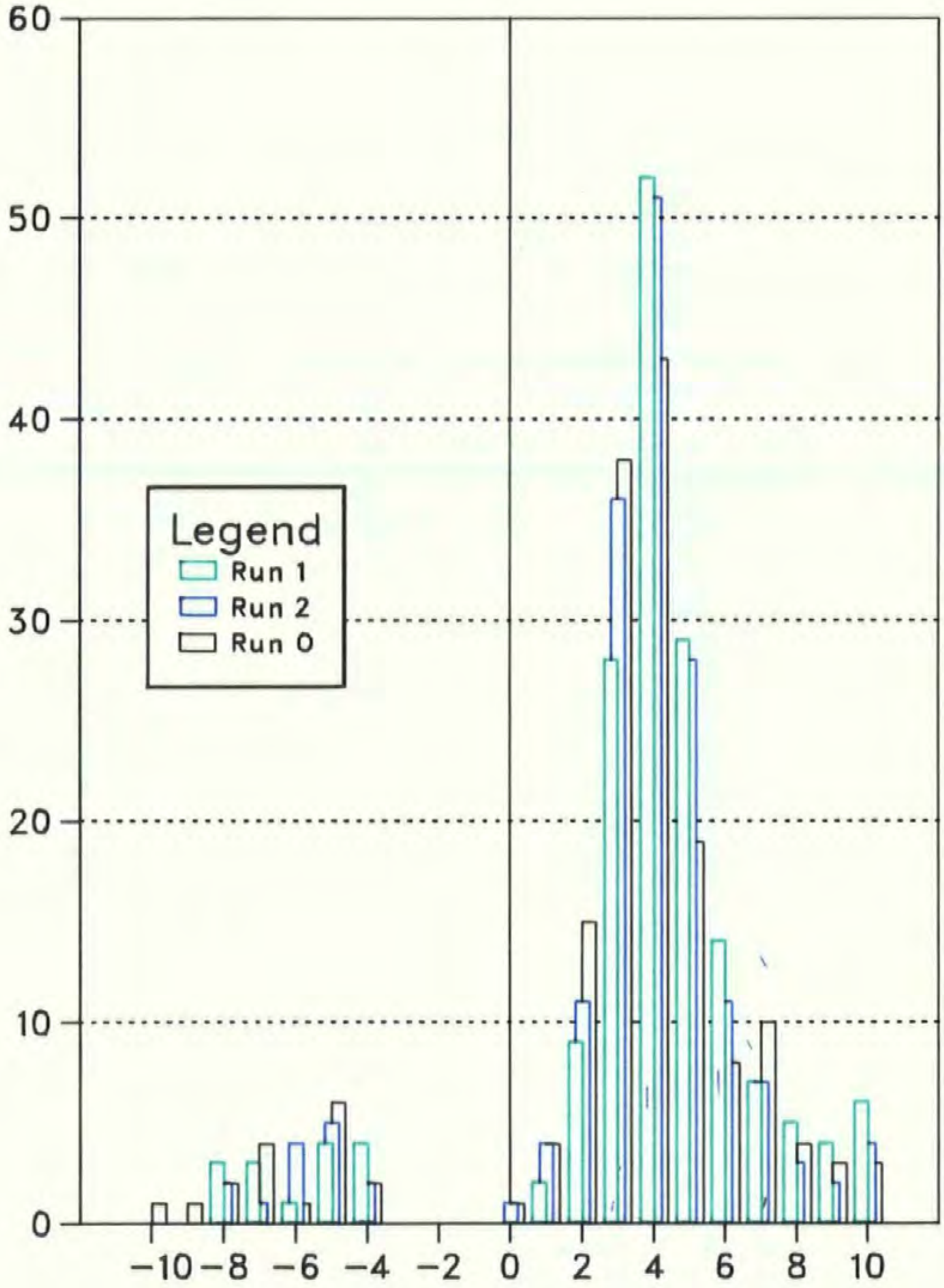
The distribution of through traffic at the Varne reflected the best agreement of all the statistical tests. Figure 7.15 shows the distributions for all three runs. It can be seen that approximately 91% of vessels passed north of the Varne in all three cases. The modal value is the same at 1 n.mile north and 1.25 n.miles south in all three cases. It can be seen further that both sets of distributions north and south of Varne are restrained within the same bounds whilst for those vessels passing north of Varne the distributions are all skewed significantly to the south. The mean passing distance north of Varne was 1.04 n.miles for Run 1 with a standard deviation of 0.47 n.miles, 1.19 with a standard deviation of 0.44 for Run 2 and 1.18 n.miles with a standard deviation of 0.47 n.miles for the observed values. It was decided to restrict the comparison using the chi-squared test to the distributions north of the Varne. This gave a total of 11 degrees of freedom. The chi-squared statistic was 22.38 for Run 1 and 12.62 for Run 2, both compared to Run 0. There is then no reason to reject the null-hypothesis at a 1% significance for Run 1 and at 30% significance for Run 2.

7.2.4 The average lateral deviation and duration of manoeuvres

7.2.4.1 The average lateral deviation

As has been explained the average lateral deviation is a measure of the efficiency of the manoeuvres executed by through traffic. The

Fig.7.15 Distribution of through traffic at Varne



agreement between the simulated and the observed results was very good. The observed through vessels were noticed to manoeuvre on average 0.67 n.miles off course. The simulated through vessels altered at an average of 0.61 n.miles and 0.65 n.miles off course for runs 1 and 2 respectively. The slightly higher value for the observed values was thought to be due to not noticing some of the slight overtaking manoeuvres which would have reduced the average figure.

7.2.4.2 The average duration of manoeuvres

The average duration is a combination of the R.D.R.R. or the time at which the initial manoeuvre was started and the point at which the vessel started to return back on to course. Again a good agreement was observed between the observed and the simulated with Run 1 recording an average duration of 5.9 minutes, Run 2 with 6.2 minutes and Run 0 with 5.6 minutes. Again the lower value obtained for the observed value was most likely due to the loss of some of the overtaking manoeuvres which are longer in duration than the other types of manoeuvres.

7.2.5 Selection of ship tracks

A selection of ship tracks have been taken from Run 2. The axes were graduated in miles, and orientated so that the x-axis ran parallel to the boundary of the main lane and the E.I.T.Z.. The times are in minutes from the start of the run and the ships' numbers are shown at the start of each track.

Figure 7.16 shows a typical overtaking encounter with ship 18 overtaking ship 17 at 200 minutes into the run. The P.C.P.A. was 0.1 n.mile and ship 18 altered course 9 minutes before C.P.A..

Figure 7.17 shows a crossing encounter with the through vessel, ship 121 altering course for the ferry from Dover, ship 132. With a P.C.P.A. of 0.3 n.miles the ship 121 altered course at 6.5 minutes before C.P.A..

Figure 7.18 displays the track history of an encounter with a ferry to Dover from Dunkerque (ship 9) altering course to come astern of a through vessel (ship 7). The broad nature of the collision avoidance manoeuvre is indicative of an encounter with a large and negative P.C.P.A. which in this situation was 0.5 n.miles. Ship 9 altered at 6 minutes before C.P.A..

Figure 7.19 illustrates a near head-on crossing encounter with a P.C.P.A. of 2 cables. Ship 36 altered course to starboard at 5 minutes before C.P.A. to leave a C.P.A. of 8 cables.

Figure 7.20 depicts another situation in which an encounter with inherent negative contribution resulted in a very broad alteration of course. Ship 161 travelling at 10 knots and with a P.C.P.A. of 4 cables ahead of ship 177, altered course at 6 minutes before P.C.P.A.. It can be seen that because it was much slower than the ferry to Boulogne (ship 177) and the encounter had negative contribution that it had to alter almost to the reciprocal course of the ferry.

Figure 7.21 shows a head-on encounter in which ship 154 altered course to starboard to avoid ship 151. It altered back to its original course and then found it clear to cross the routing scheme at time 1120.

Figure 7.22 displays a multi-ship encounter, with the crossing vessel bound for the Sunk area altering course initially for ship 48 and then finding itself in a head-on encounter with ship 49. It can be seen that in this particular situation ship 49 altered course to starboard to further increase the miss distance.

Finally figure 7.23 shows a situation in which several encounters were observed to take place. Ship 94 overtakes ship 92 to starboard and then overtakes ship 90 to port. Ship 92 alters course to crossing ferry 97. Ship 90 alters course for the ferry from Dover to Calais (ship 102) and then alters again for the ferry from Folkestone to Boulogne (ship 104).

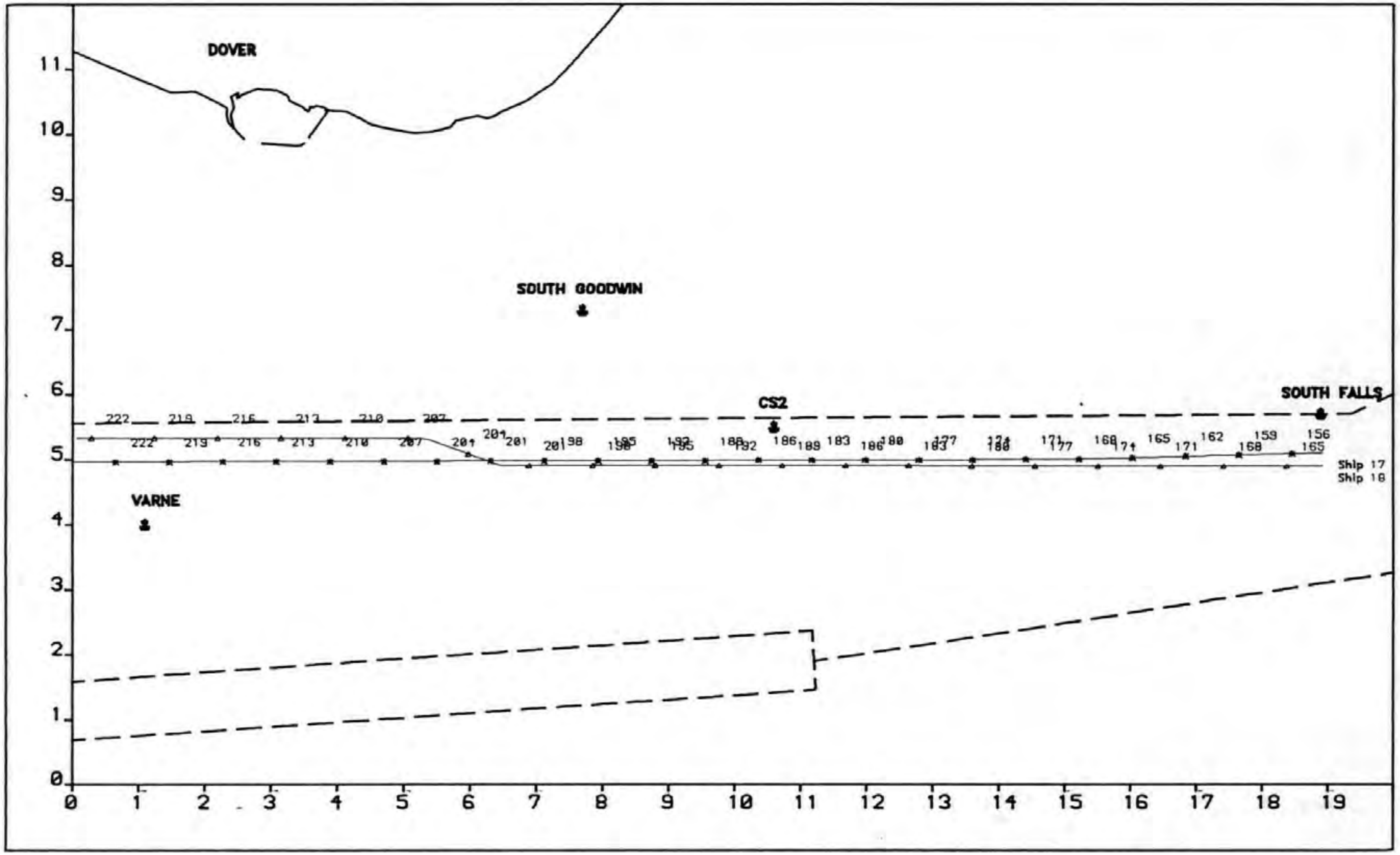


Fig. 7.16 Overtaking encounter

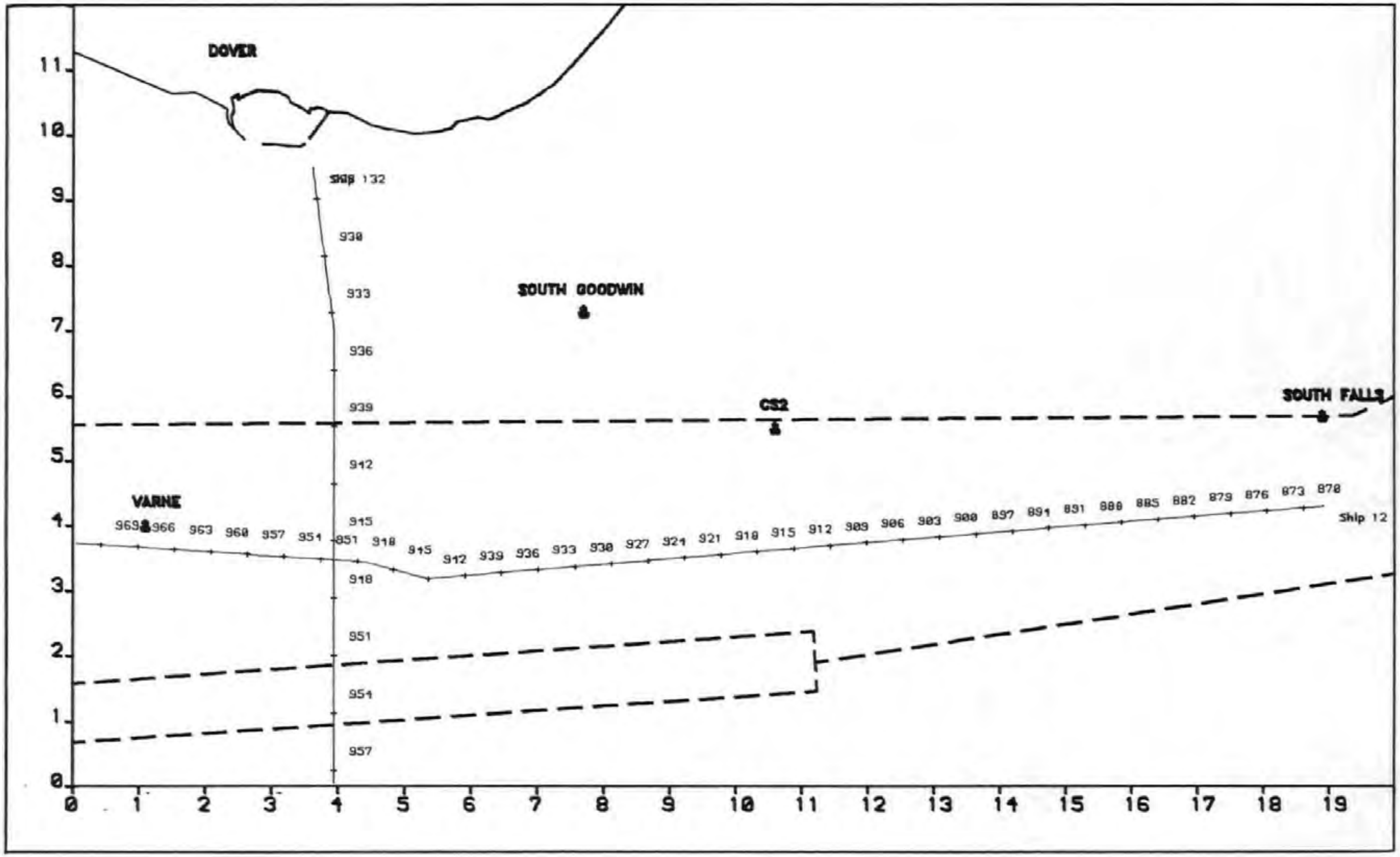


Fig. 7.17 Crossing encounter with through vessel give-way

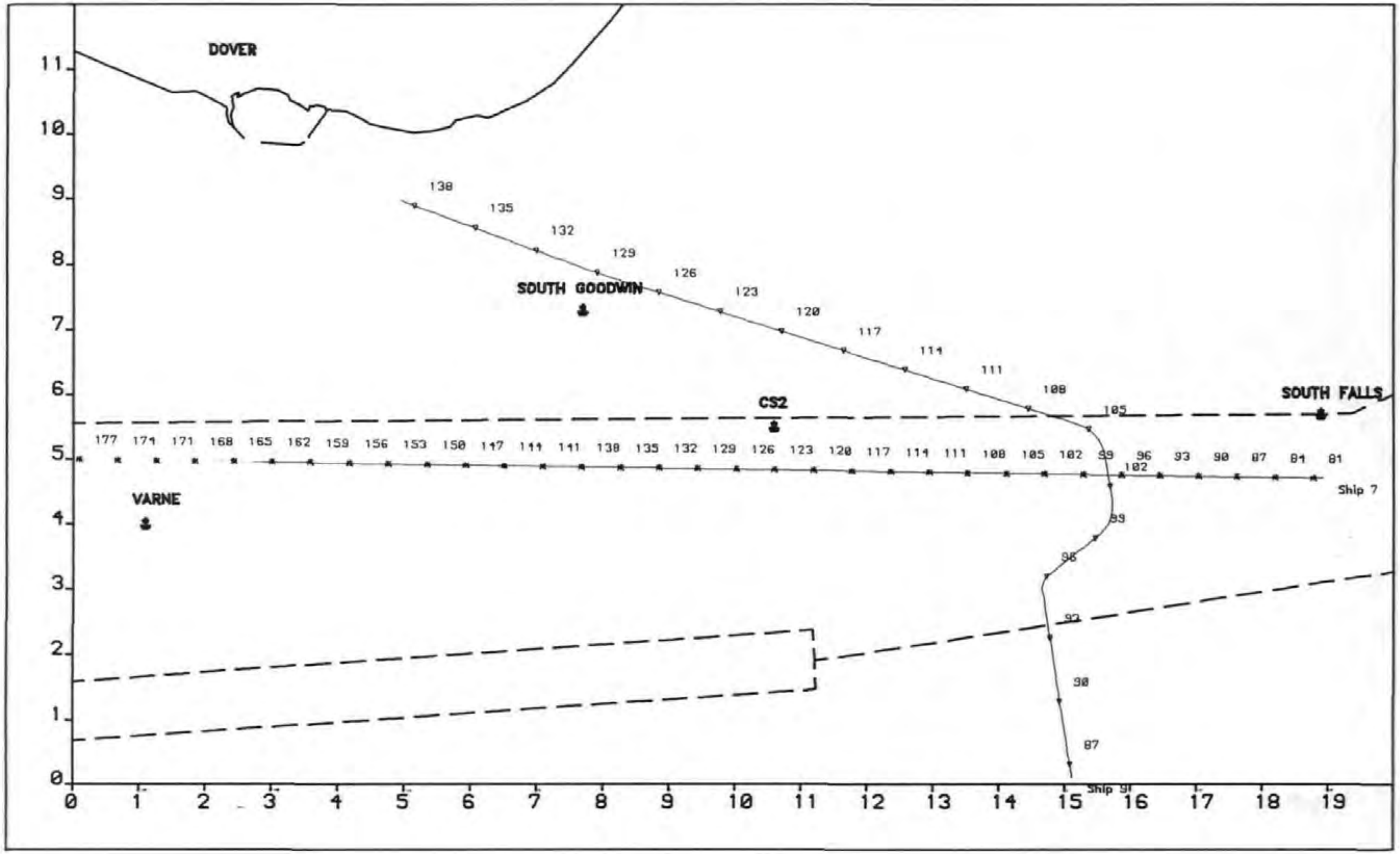


Fig. 7.18 Crossing encounter with ferry from Dunkerque give-way

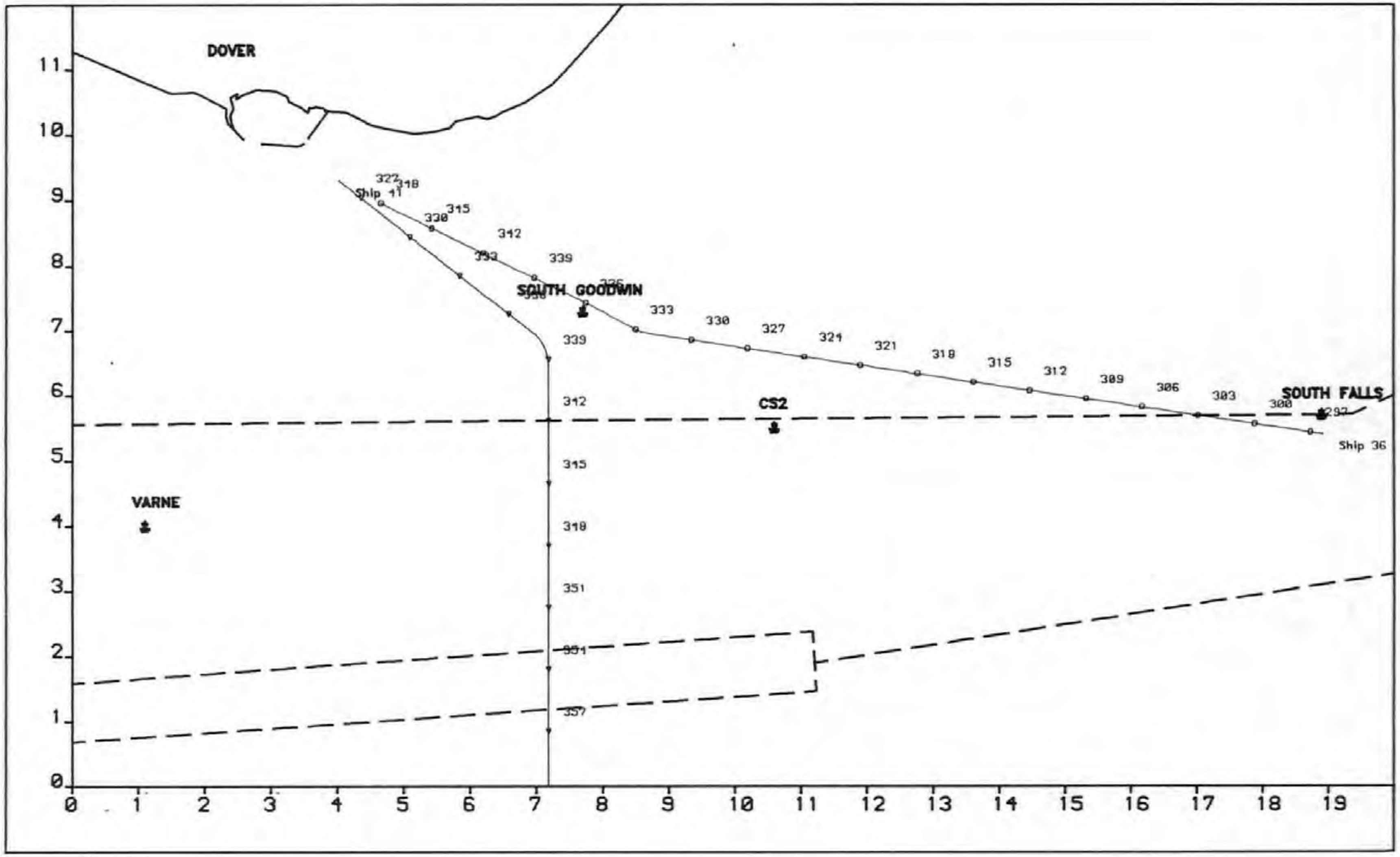


Fig. 7.19 Near head-on crossing encounter

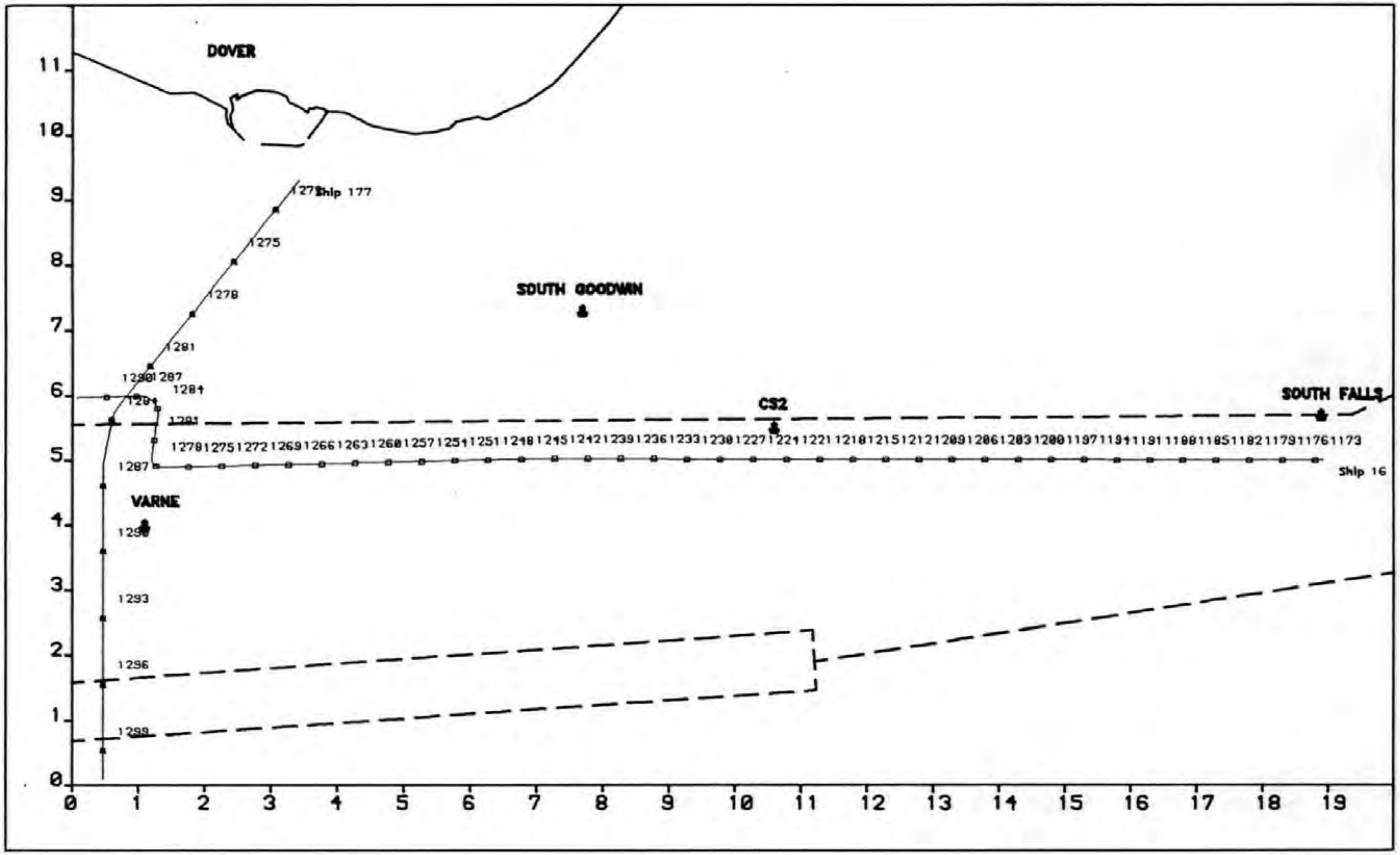


Fig. 7.20 Crossing encounter with a slow through vessel give-way

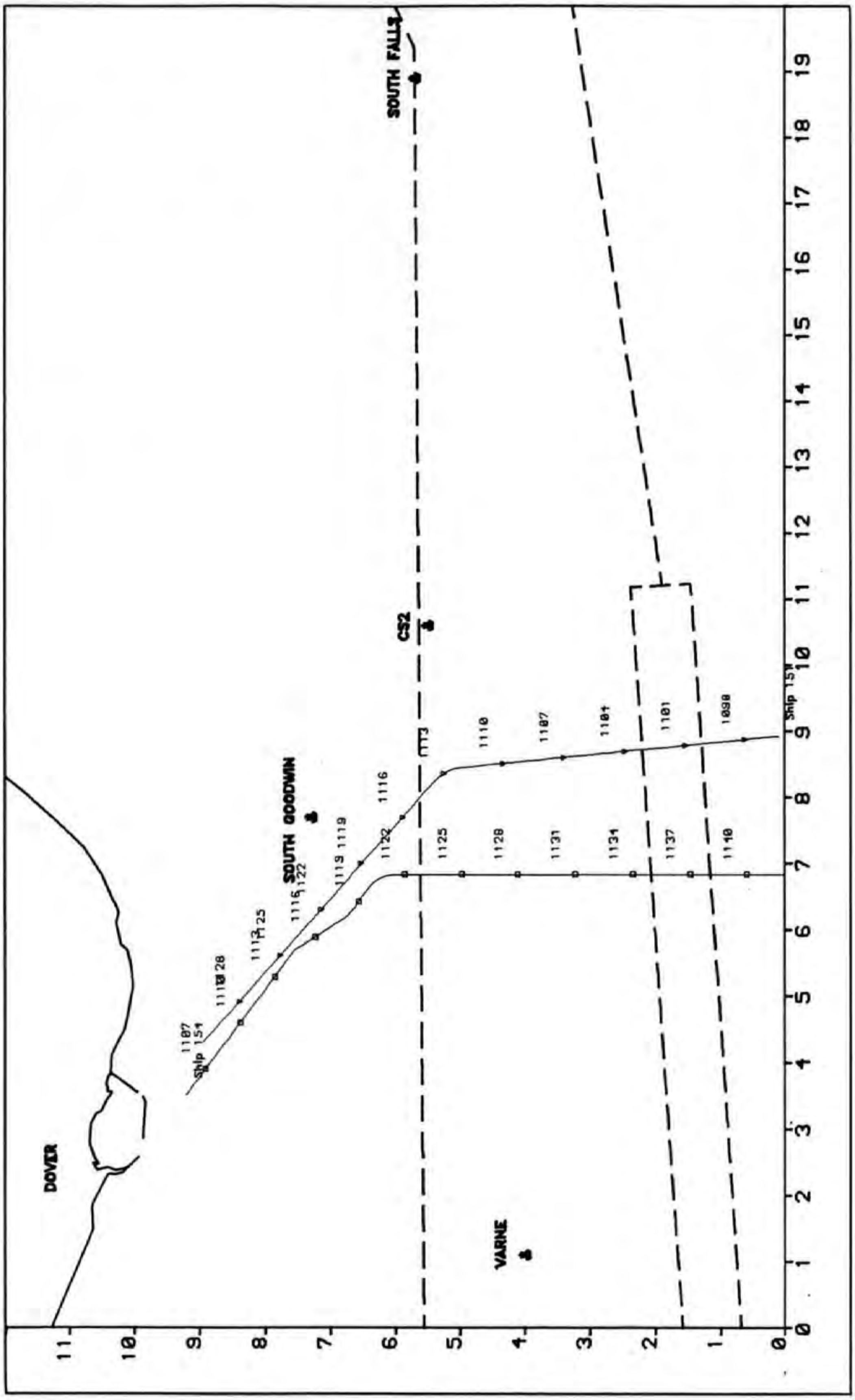


Fig. 7.21 Head-on encounter between crossing ferries

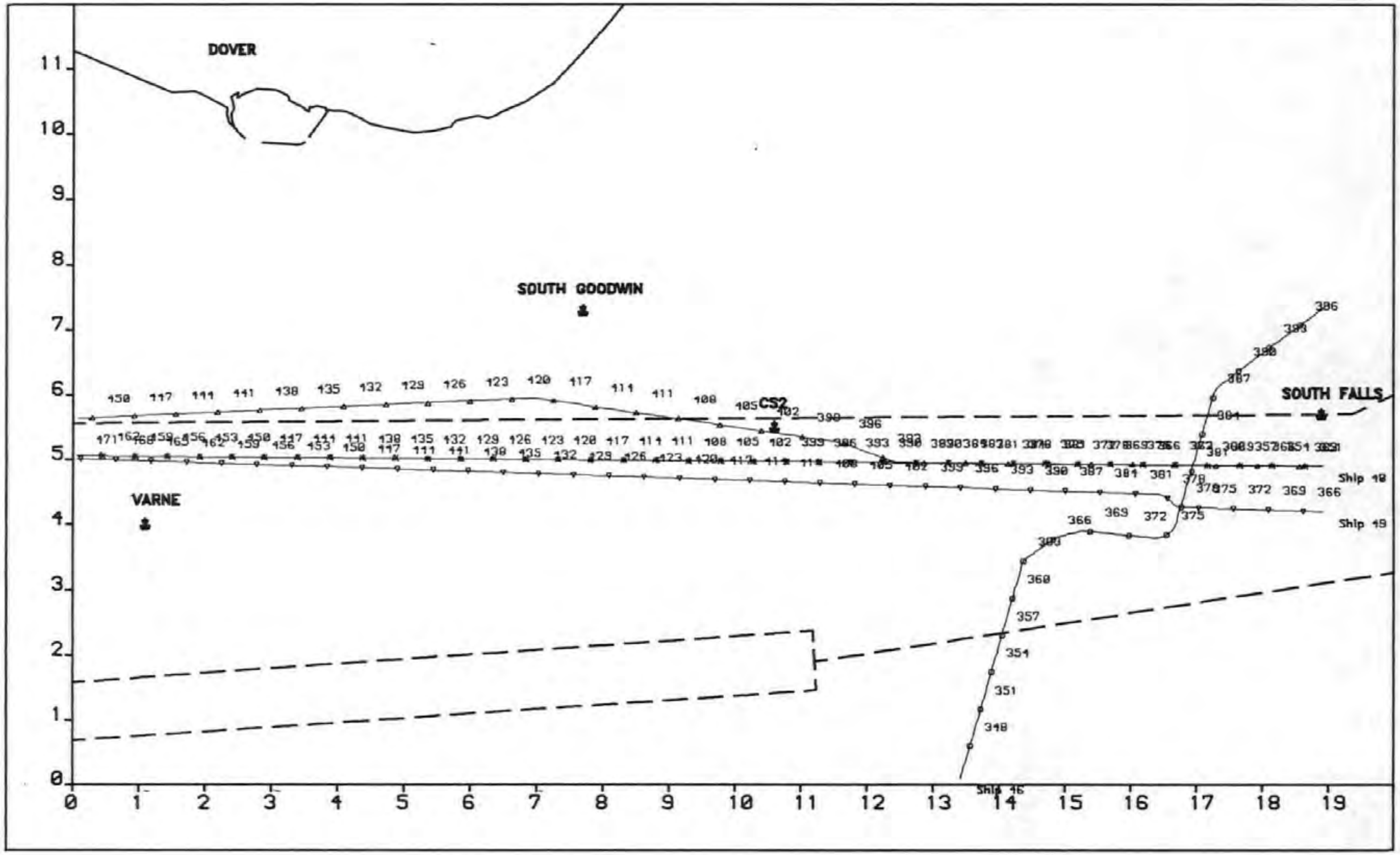


Fig. 7.22 Crossing vessel forced to make several collision avoidance manoeuvres

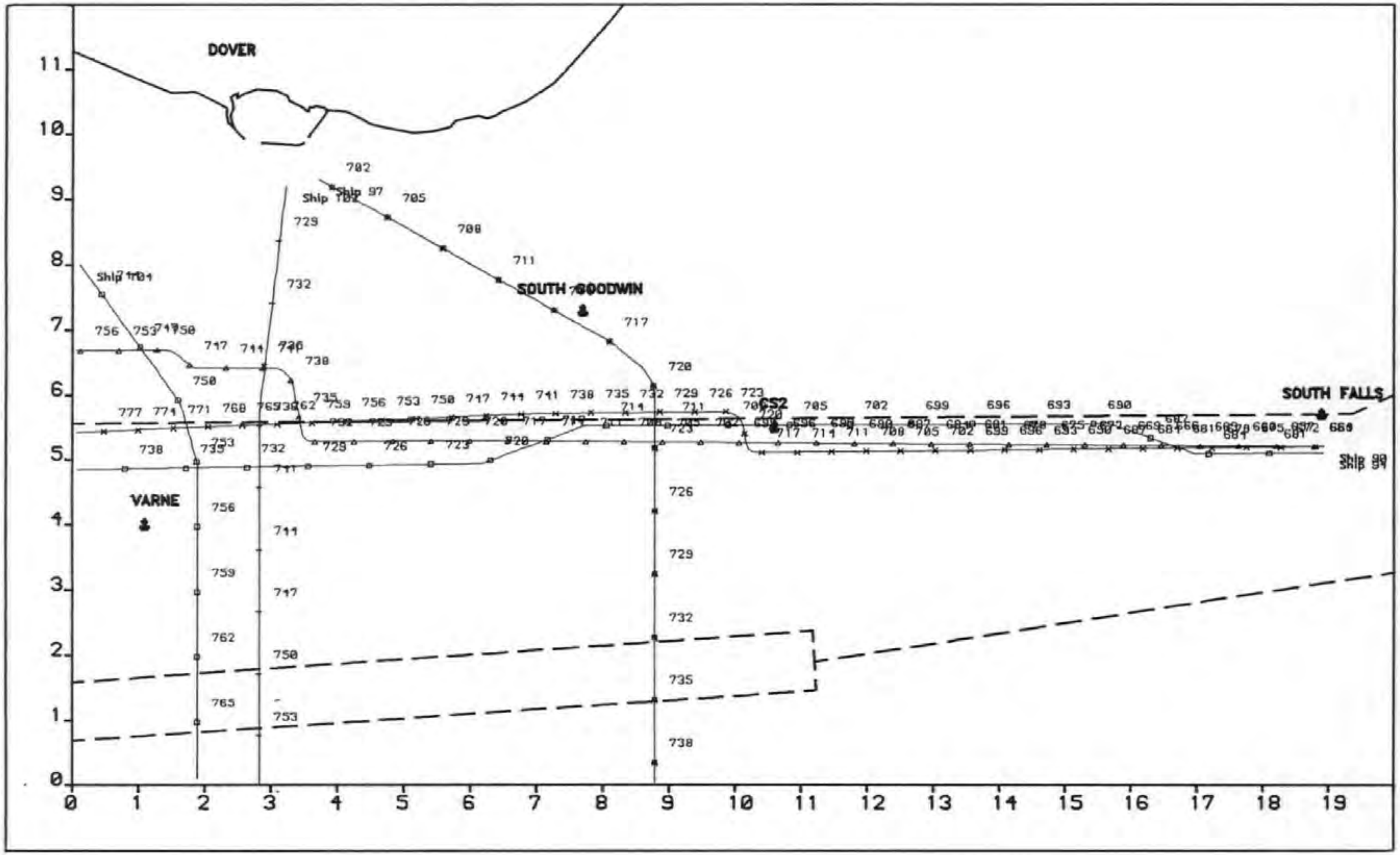


Fig. 7.23 A large selection of encounters

7.3 Conclusion

It can be seen that some aspects of the validation were corrupted due to the inadaquacies of the original data against which comparisons were made. In particular the difficulties in recognizing when an overtaking manoeuvre had taken place and the problems in recording all possible combinations of C.P.A.s between vessels, when groups of six or more travelling down the main lane in a bunch were not uncommon, resulted in significant errors in the observed data. It has been shown however that if the overtaking encounters were not included in the analysis that the results were in general valid. The good agreement between the two distributions for through vessels at the Varne suggest that the number and degree of manoeuvres and the navigation course alterations by main lane traffic were broadly similar. This was further justified by the similarities between the average lateral deviation of manoeuvres and the total time taken to complete the manoeuvre sequence.

As a final qualitative assessment the ship tracks shown in Figures 7.16 to 7.23 were shown to the majority of mariners who had taken part in the computer controlled radar simulator exercises (Chapter 9). In all cases the results were thought to be realistic. Some comments were made concerning the difficulty in reading some of the times, particularly in Figures 7.22 and 7.23, but there were no criticisms of the vessels' manoeuvring or navigational characteristics, apart from two concerning Figure 7.20. In this situation two of the mariners thought that the ferry would have altered course to come astern of the main lane vessel immediately on leaving Dover.

Chapter 8 The computer simulation as a predictive aid

8.1 The effects of compulsory stand-on action

8.1.1 Reasons for implementation

One of the more interesting questions that might be resolved by the computer simulation is: "what effect does the collision avoidance action of through vessels have on the system as a whole ?". It was thought that an obvious method of evaluating this action would be to compare the system outputs from the simulation run using the generated data (Run 2) with the same run without allowing any collision avoidance action (Run 2a).

8.1.2 The distribution of through traffic at the Varne.

One effect to be considered was how manoeuvres by through vessels might produce variations in the distributions of through traffic at the Varne. Clearly the resulting distribution should be a function of the amount by which vessels were forced to manoeuvre either to port or to starboard. It would not be solely a function of the amount of lateral deviation due to collision avoidance action, because a vessel altering to a position off its normal track could find itself easily with a new desired course, via the direction grid. For example a vessel initially intending to pass north of the Varne on altering course to port to overtake a vessel might then prefer to alter course to pass south of the Varne. Clearly in all crossing situations the give-way vessel alters course to starboard, whilst in the overtaking encounters the option exists to overtake either to port or to starboard. In the majority of encounter situations a vessel will however alter course to starboard. The result of this bias to starboard should then result in a skew in the distribution to the north. The effect of no collision avoidance manoeuvres on the distribution of through traffic at the Varne is shown in Fig.8.1. The initially predicted result of a skewing to starboard can be seen clearly with a mean distance for traffic passing north of the Varne of 1.19 n.miles as opposed to that of 1.04 for the no manoeuvring run. This would indicate that the majority of manoeuvres were to starboard. The variation in the distributions was also significant as could be seen by comparing the standard deviation of 0.44 n.miles for Run 2 as opposed to 0.20 for Run 2a.

8.1.3 The distribution of the number of encounters

Clearly since no manoeuvres were permitted for Run 2a there was a requirement to redefine the meaning of encounter in this situation. It was decided then to revert to the earlier definition which stated that an encounter had taken place if a vessel's domain was infringed. The facility was introduced then to flag an infringement of the relevant domain by a target and hence to count the total numbers of each type of encounter. One difficulty with this however was that since the model only considered whether a vessel was threatening when it came within "radar range", some of the potential encounters could have been lost.

Fig.8.1 Distribution of through traffic at Varne

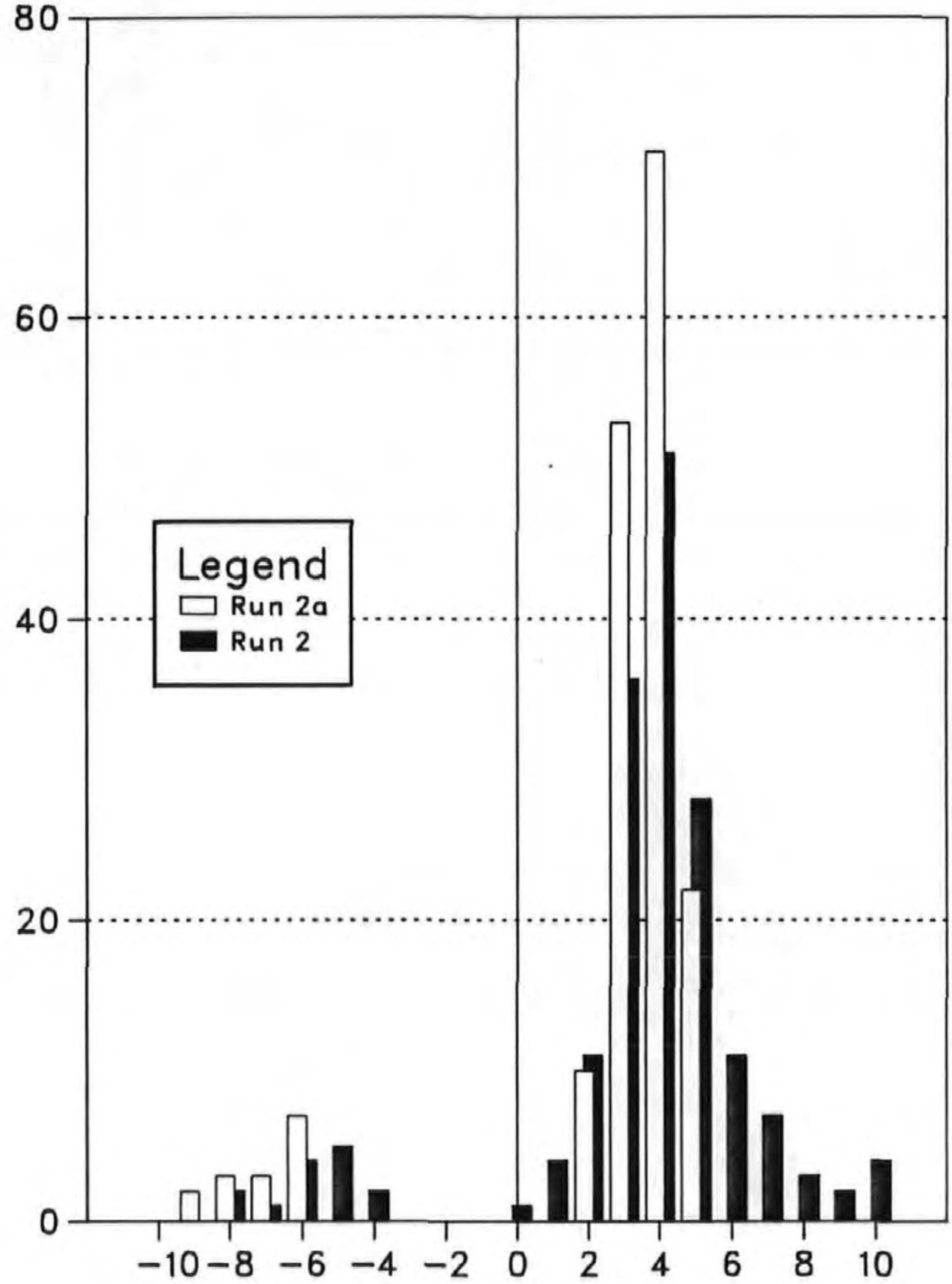


Figure 8.2 shows the distribution of all the encounters. It can be seen that the increase in the total number of encounters in Run 2a was slight, with the number of crossing encounters increasing and the number of head-on encounters decreasing. It was thought that in general the total number of encounters, which was governed essentially by the constraints of the system and the number of vessels, would remain constant. A possible explanation for the increased number of crossing and reduced head-on encounters was that the early action by crossing ferries to cross the routing scheme at 90 degrees transformed what would have been fine-crossing encounters to head-on encounters.

8.1.4 The spatial distribution of encounters

Figures 8.3a-d illustrate the spatial distribution of encounters. It can be seen that the spatial distribution of the total number of encounters (Figure 8.3a) follows much the same pattern as Run 2, with the high density of main lane traffic and the fan of vessels from Dover. The head-on encounters distribution (Figure 8.3b) was included solely to complete the set, with no conclusions possible from the two recorded encounters.

8.1.5 The distribution of the numbers of C.P.A.s

Figures 8.4 to 8.7 show the distribution of C.P.A.s for all, head-on, crossing and overtaking encounters respectively. An interesting effect is the very obvious reduction in the number of C.P.A.s up to

0.3 n.miles in Run 2. This was thought to be a direct result of collision avoidance action. Of further interest was how the effective displacement of the number of smaller C.P.A.s was reflected by an increase in the number of greater C.P.A.s. It can be seen that by far the most dramatic increase was due to the effect of overtaking action with the number of C.P.A.s less than 0.3 n.miles being reduced from 53 occurrences in Run 2a to 2 in Run 2.

A secondary observation to be considered was the shape of the distributions for Run 2a. Little can be derived from the head-on C.P.A.s but the shapes of both the crossing and the overtaking results are noteworthy. It can be seen in Figure 8.6 that the distribution of crossing C.P.A.s remained remarkably constant. This was to be expected since one random stream of traffic (through traffic) was interacting with another stream. The same was not true for overtaking encounters which, although a result of the interaction of random traffic was a function of only the one stream. This meant that although it was not constrained by any form of scheduling it was constrained by the vessels attempting to remain inside a navigable channel. This can be seen by the large number of small C.P.A.s decreasing with increasing separation.

8.1.6 The spatial distribution of C.P.A.s

The most interesting point to note from this analysis is that there still exists the broad fan of traffic from Dover and the dense pattern due to through vessels (Figs. 8.8a-b). As would be expected the patterns for C.P.A.s less than or equal to 1.0 n.mile is very similar to that for 0.6 n.miles or less.

8.1.7 Track plot of simulated traffic

Figure 8.9 shows the track plots of simulated traffic over a 48 hour period. No other 48 hour track plots have been included in the validation as in general little information can be gleaned from the graphical output. The broad fan of traffic to and from Dover can be seen clearly, along with the secondary fan to and from Folkestone. The traffic up to and from the Sunk area can be detected as can the dense through traffic. The buoys and light-vessels are depicted as triangles and the routing scheme boundaries as a dark line.

Fig.8.2 Distribution of encounters

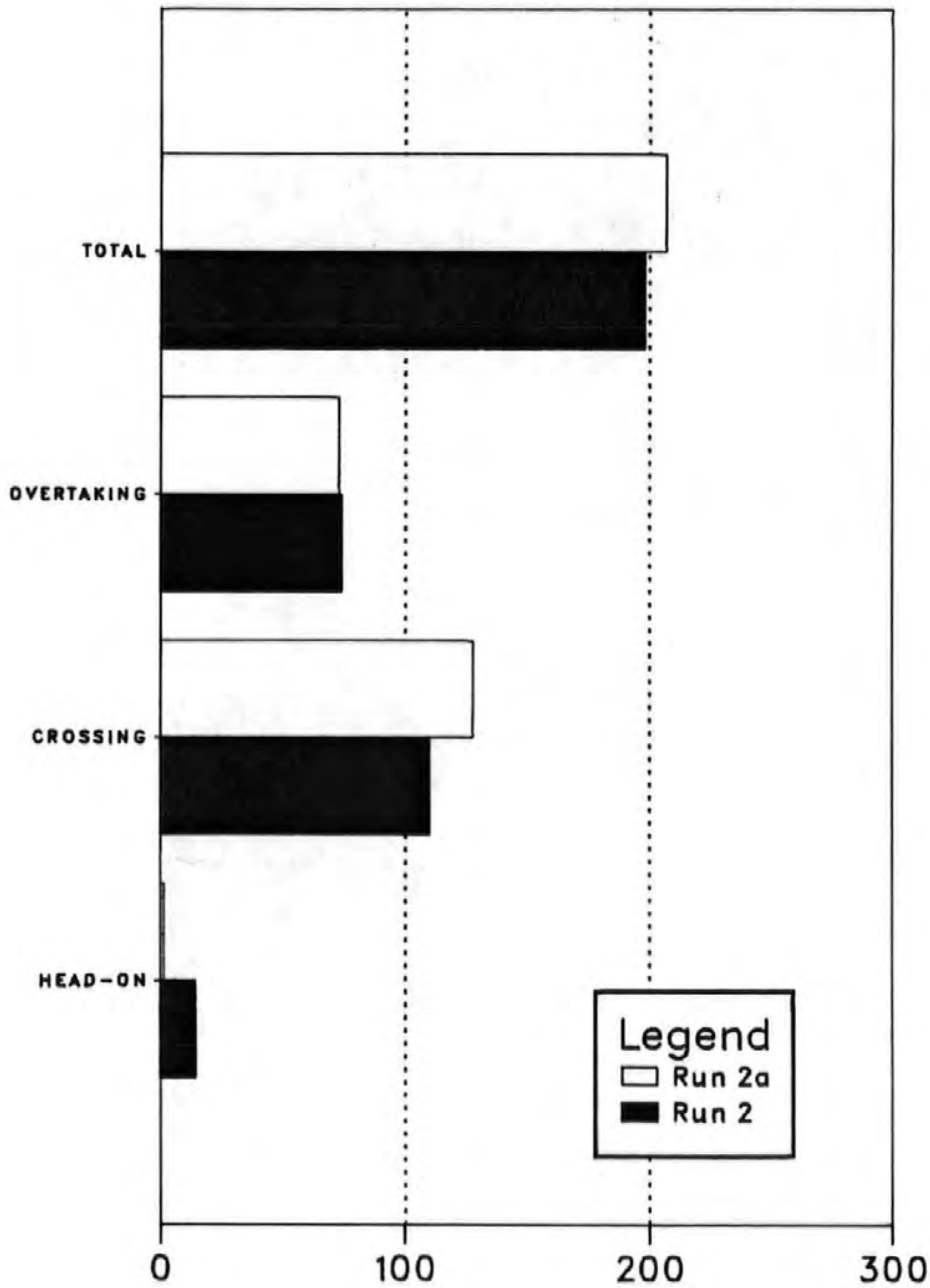


Fig.8.3a Run 2a – All encounters

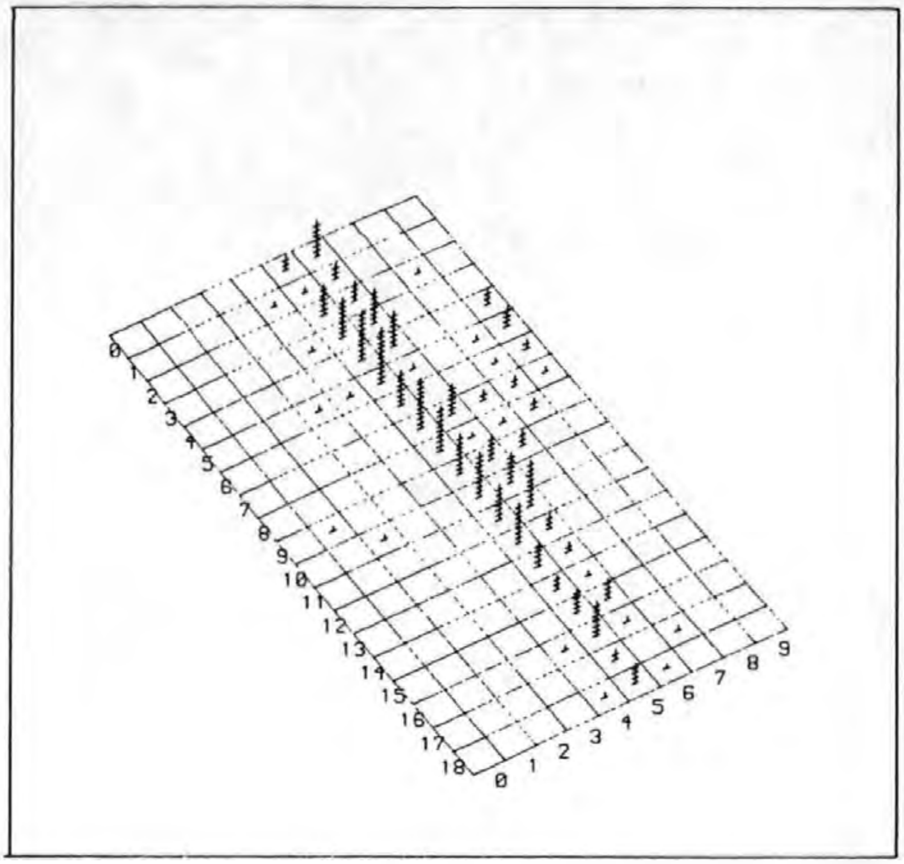


Fig.8.3b Run 2a – Head–on encounters

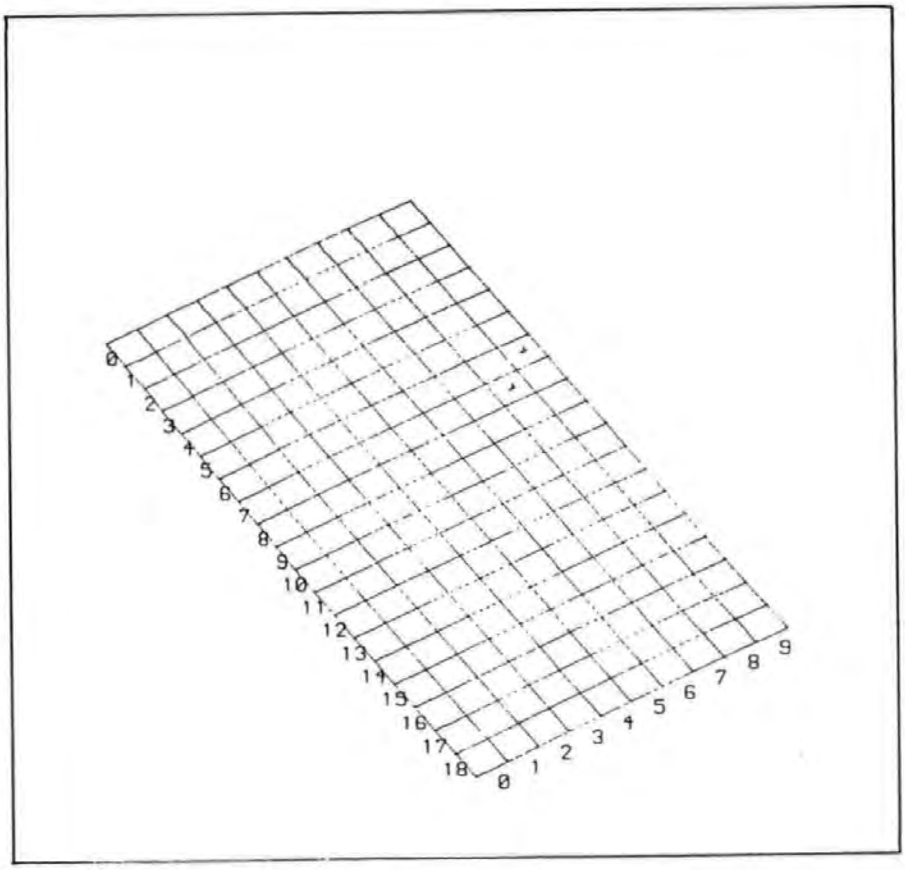


Fig.8.3c Run 2a – Crossing encounters

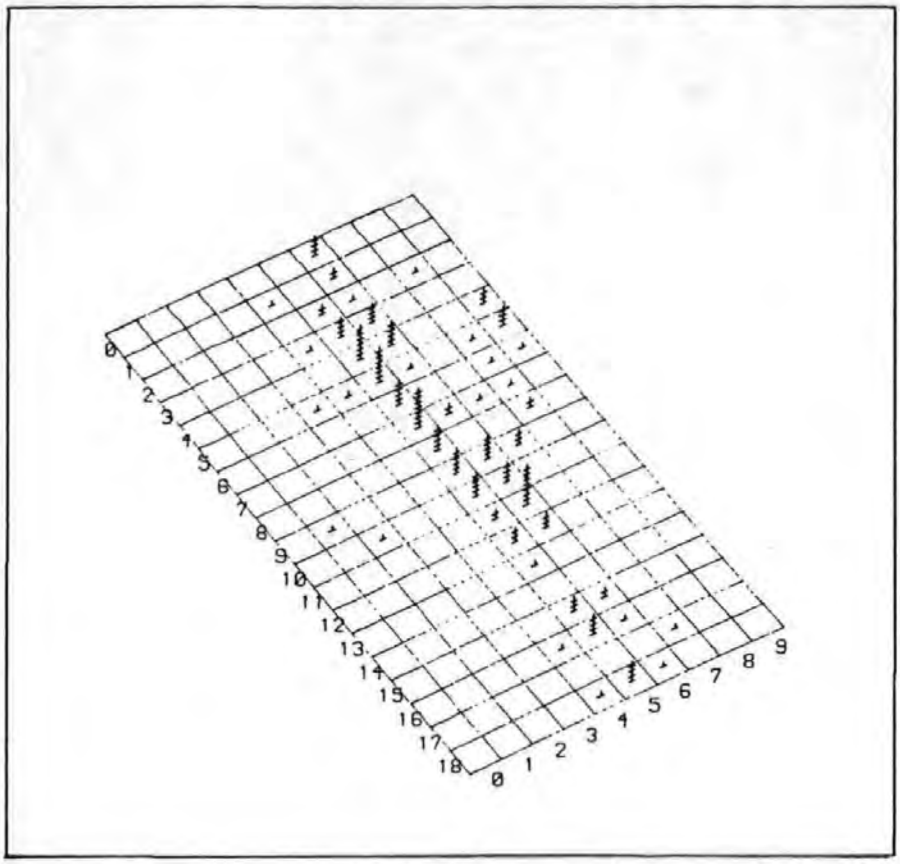


Fig.8.3d Run 2a – Overtaking encounters

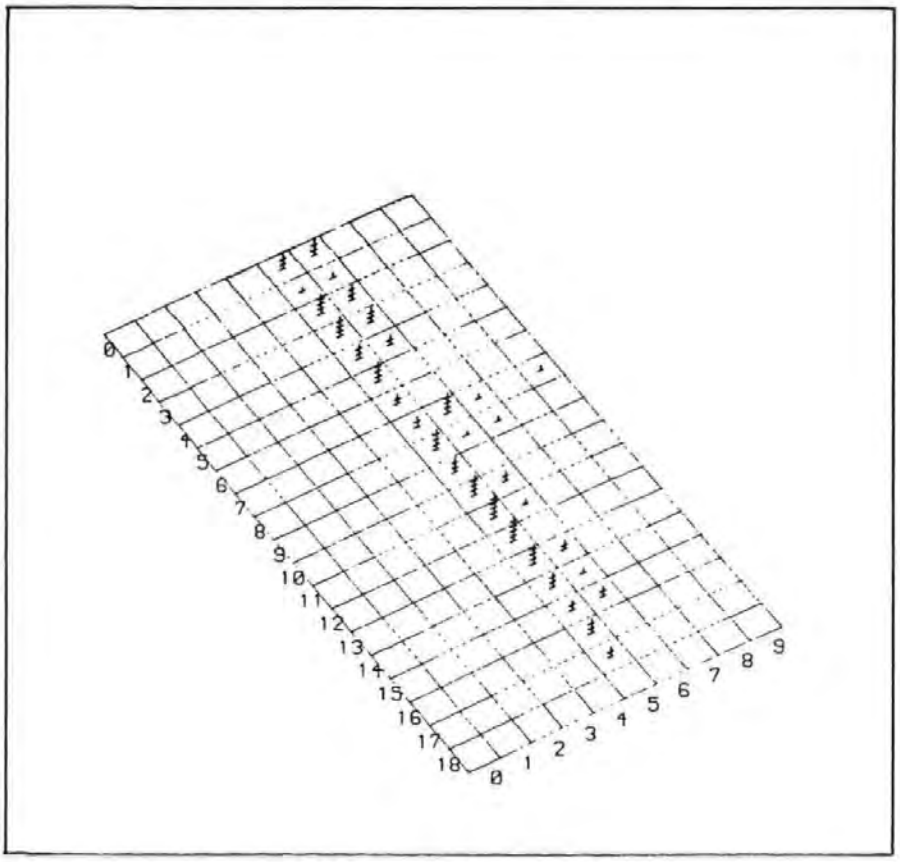


Fig.8.4 Distribution of C.P.A.s for all encounters

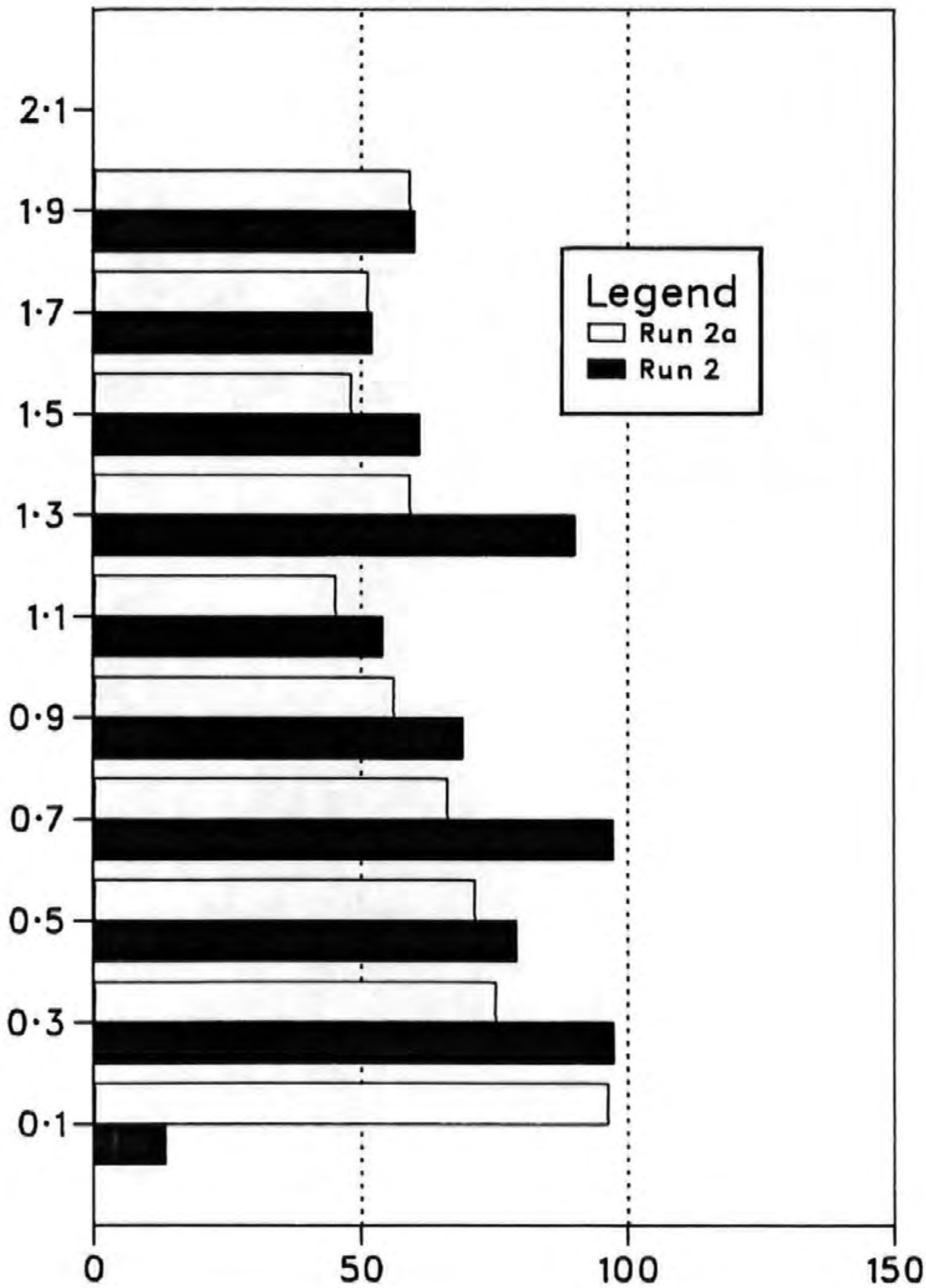


Fig.8.5 Distribution of C.P.A.s for head-on encounters

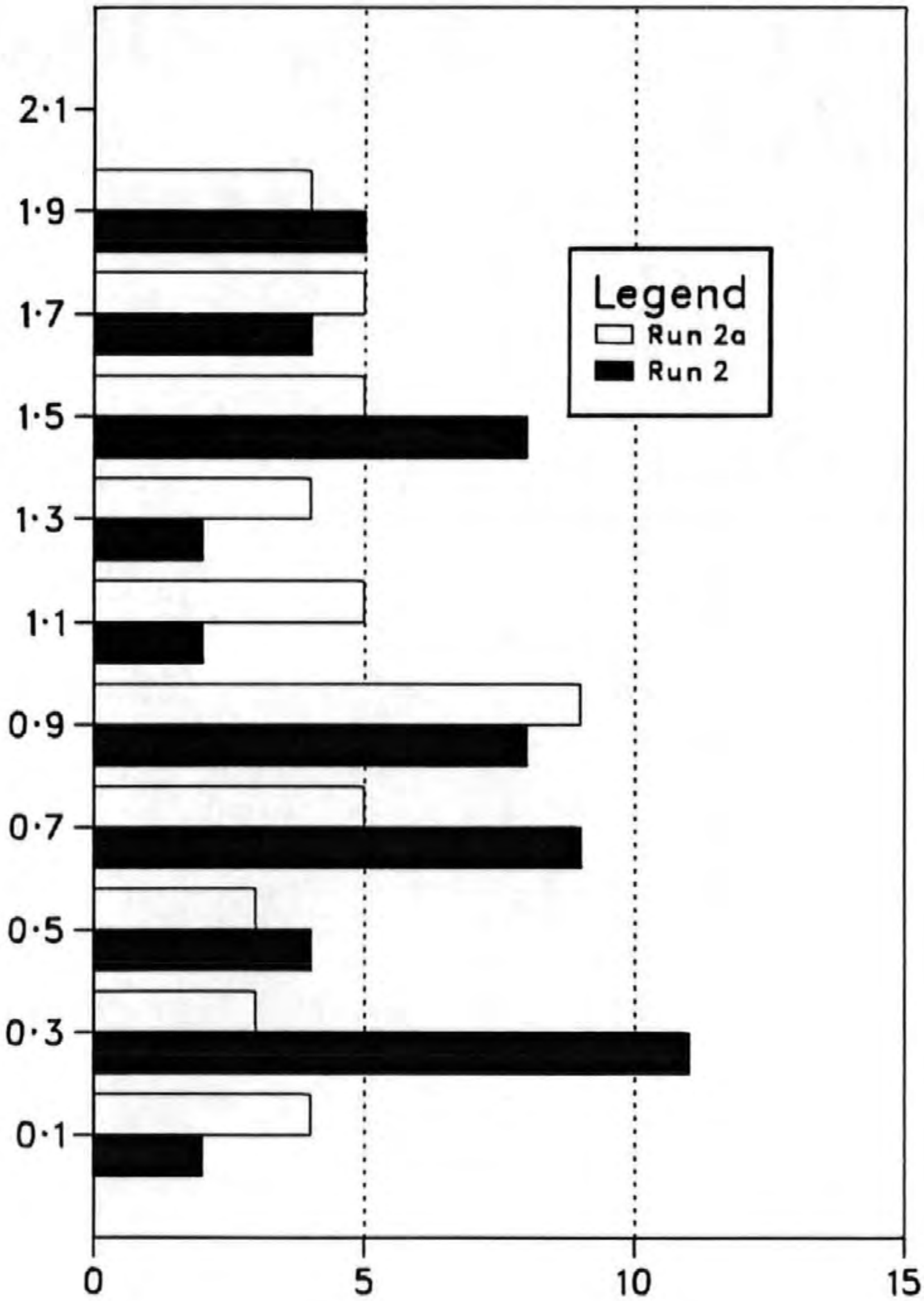


Fig.8.6 Distribution of C.P.A.s for crossing encounters

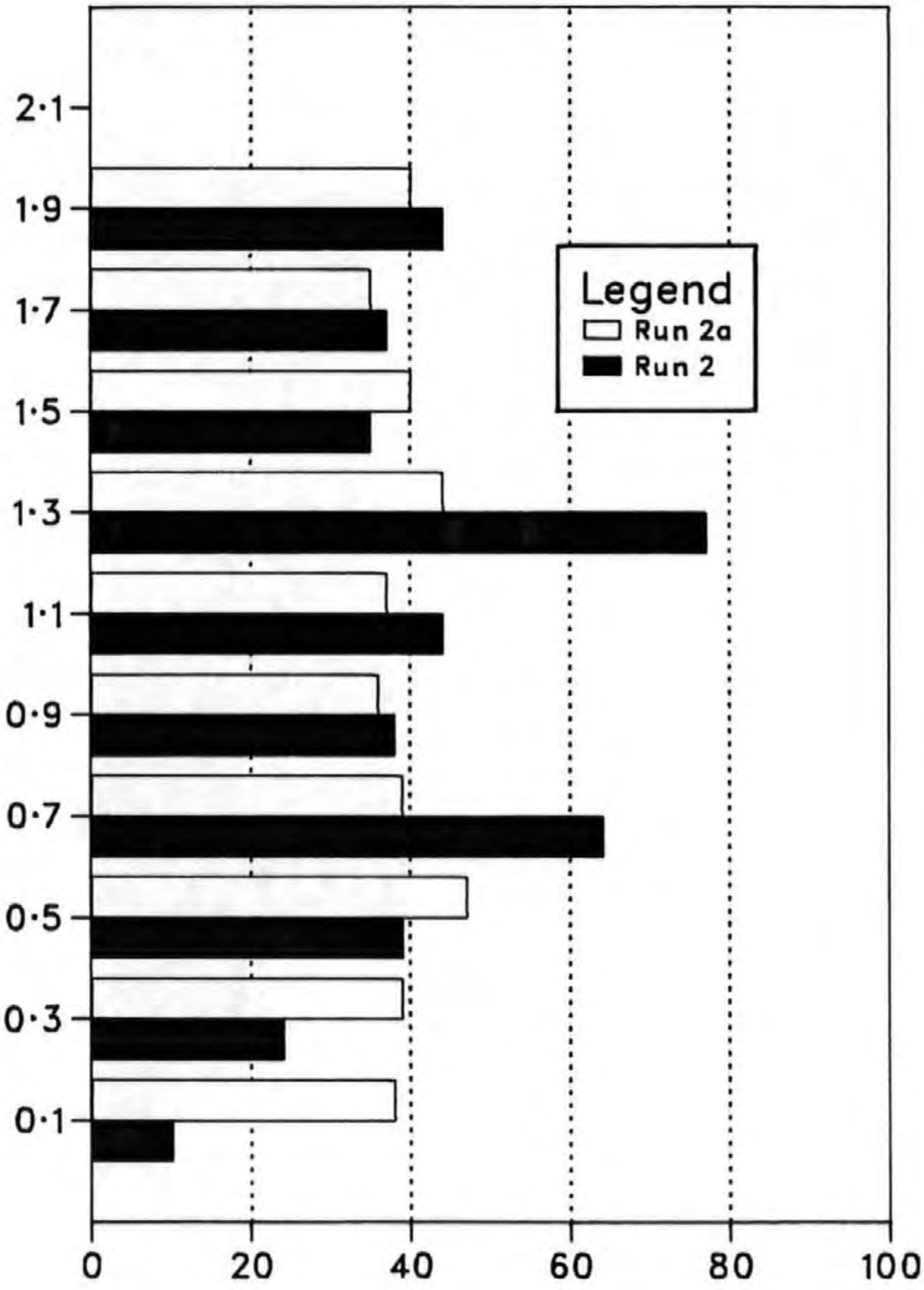


Fig.8.7 Distribution of C.P.A.s for overtaking encounters

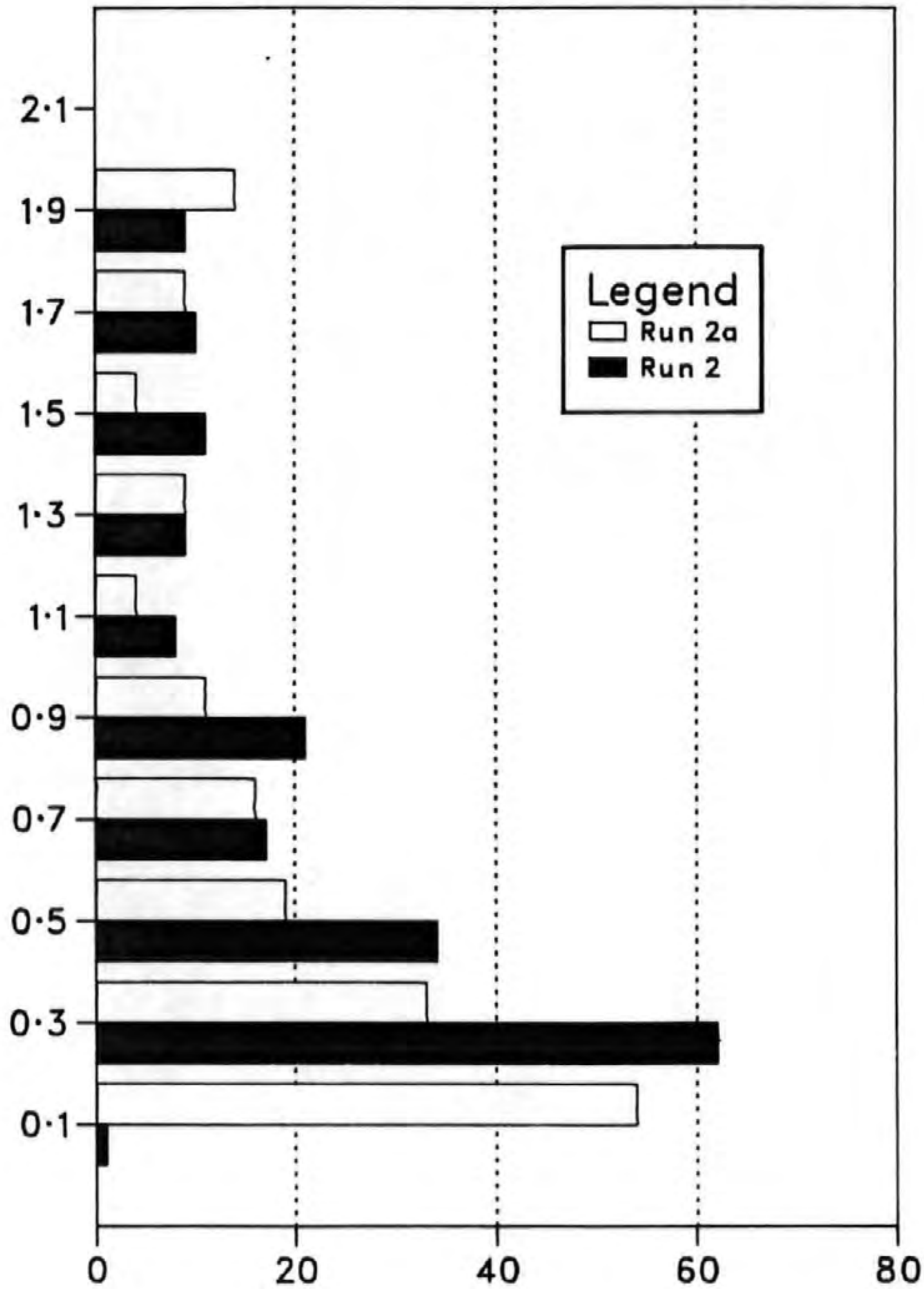


Fig.8.8a Run 2a - C.P.A.s <= 1.0

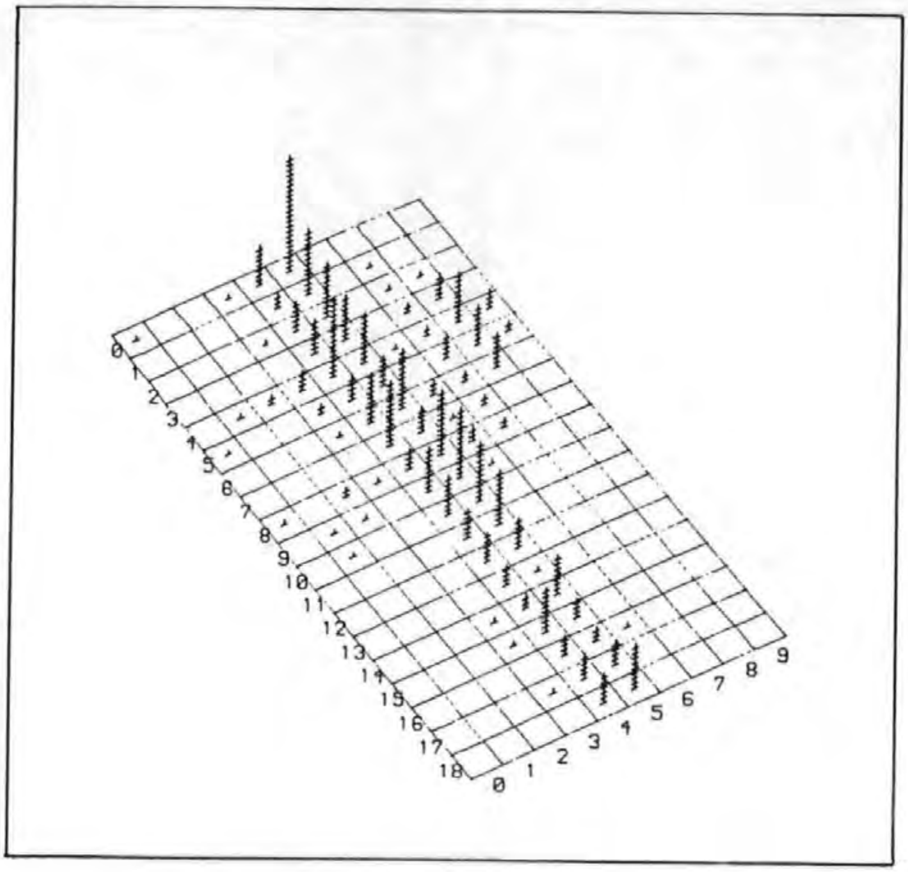
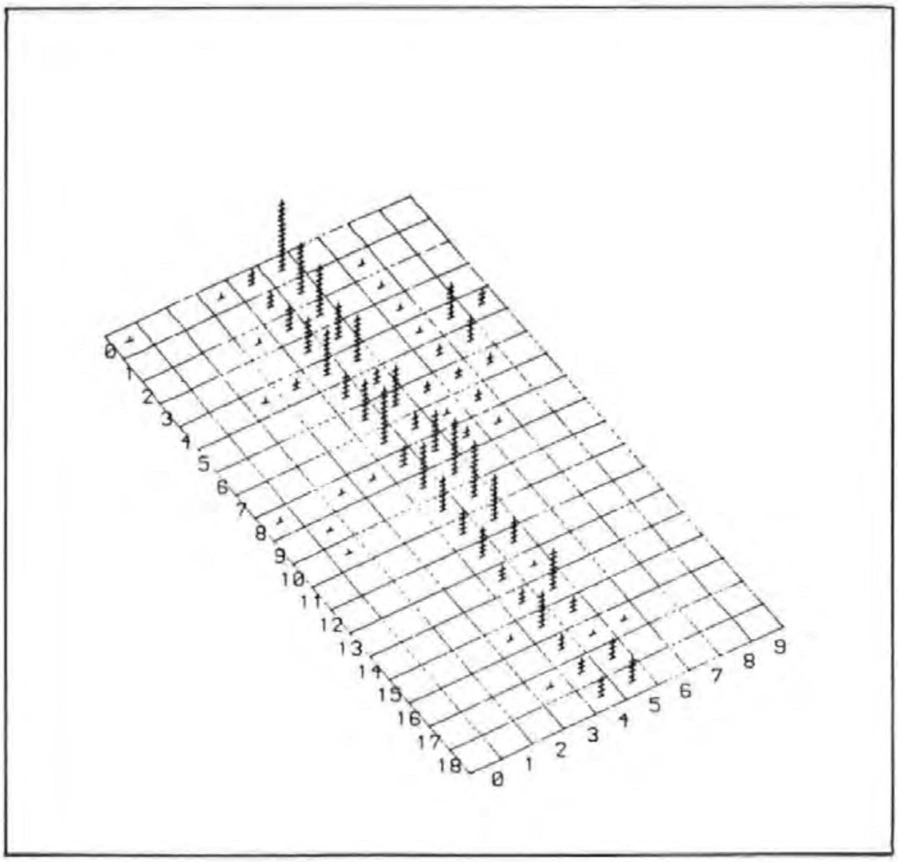


Fig.8.8b Run 2a - C.P.A.s <= 0.6



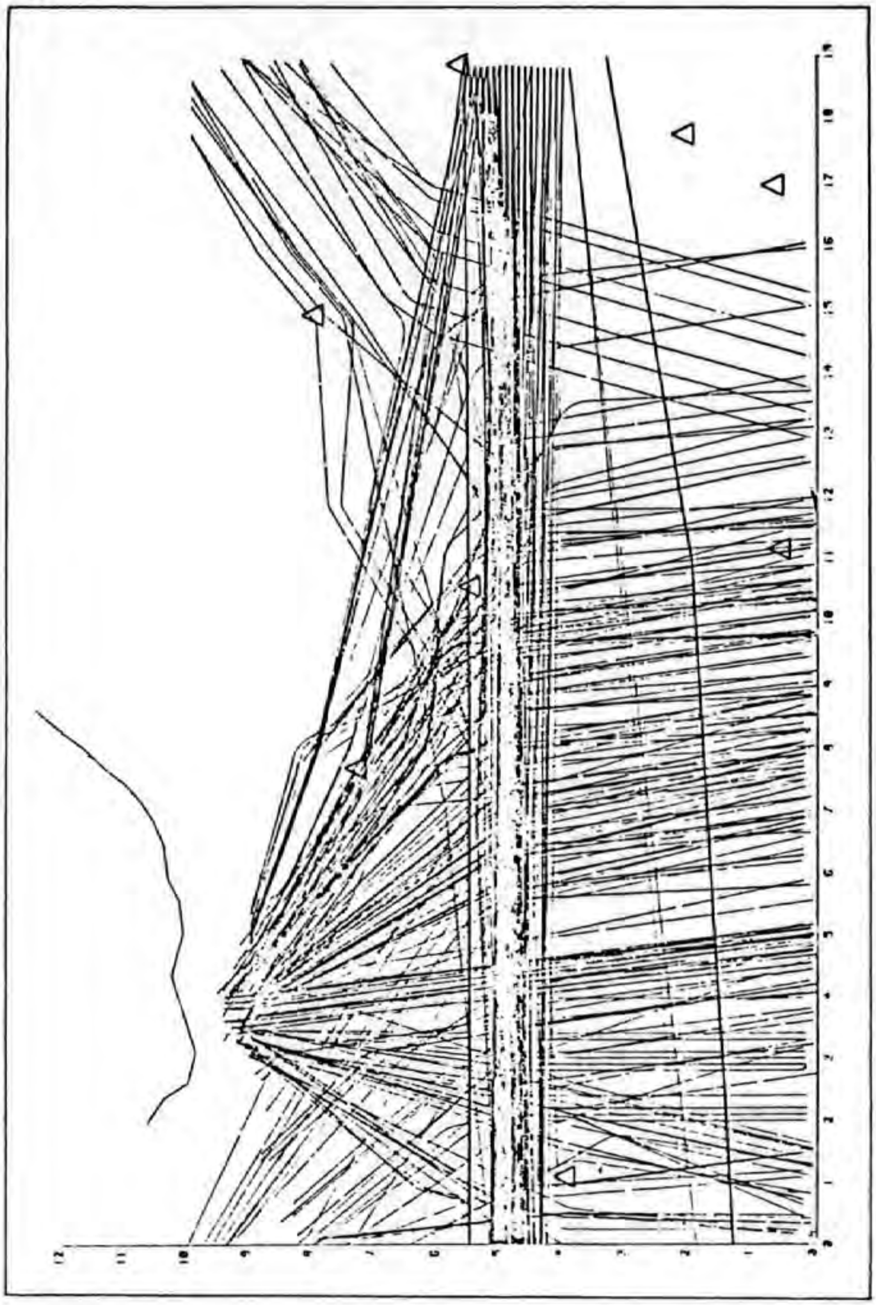


Fig.8.9 Tracks of simulated traffic with no collision avoidance action

8.2 The introduction of through rogues

8.2.1 Introduction

The main reason for introducing traffic separation to the Dover Strait was in order to reduce the number of head-on encounters between vessels. One of the most interesting ways in which this model can be used is to consider the effect of through rogues (vessels steaming directly against the main traffic flow). Although in practice there is rarely more than one through rogue per day it was thought that the best method of considering the effect of the through rogues was to input one into the system every hour. The result being that there was nearly always one rogue in the scheme at any time. There were two possible types of rogue vessels to be considered: the non-manoeuvring and the manoeuvring rogues. As a result two runs were implemented: Run 2b which input one non-manoeuvring rogue per hour and Run 2c which input one manoeuvring rogue per hour over a 48 hour period. The rogue vessels' entry points to the scheme were uniformly distributed in a range from 0.5 n.mile to 1.5 n.mile north of the Varne.

8.2.2 The distribution of through vessels at the Varne.

Figure 8.10 displays the distribution of through vessels at the Varne. The most obvious effect for both runs is to spread the distribution and to shift it to the north. As would be expected the most pronounced effect was for the non-manoeuvring rogues (Run 2b). Vessels passing north of the Varne left a clearance to the light-vessel of 1.35 n.miles for Run 2b, 1.36 for Run 2c as opposed to 1.19 for Run 2. It was found that the spread of the distributions for vessels passing north of the Varne remained remarkably constant at 0.44 n.miles for all three runs.

8.2.3 The distribution of the number of encounters

Of greater significance than the lateral distribution of through traffic was the effect on the number of encounters. Figure 8.11 shows the distribution of the number of encounters. It can be seen that the total number of encounters more than doubled with the introduction of rogues, with the greatest increase being for the manoeuvring rogues. The most significant point to note is that the increase was almost totally due to the increased number of head-on encounters.

8.2.4 The spatial distribution of encounters

Figures 8.12a-d show the spatial distribution of encounters for the non-manoeuvring rogues whilst Figures 8.13a-d show the same results for the manoeuvring rogues. In both sets of data attention must be drawn to the heavy band of head-on encounters occurring in both 8.12b and 8.13b. Also of interest is the spread into lane 3 of the crossing encounters for the manoeuvring rogues (Fig. 8.13c). This is indicative of the through rogues altering course to starboard for ferries to Dover and Folkestone.

8.2.5 The distributions of the number of C.P.A.s

Figures 8.14 to 8.17 show how the C.P.A.s are distributed. On considering Figure 8.14 which looks at the distribution for all encounters, it can be seen that the total number of C.P.A.s almost doubled for the non-manoeuvring rogues and very nearly doubled for the manoeuvring rogues. It can be seen further that the most extreme differences were for the head-on encounters (Fig. 8.15).

8.2.6 The spatial distribution of C.P.A.s

Figures 8.18a-b and 8.19a-b show the distributions of C.P.A.s for both sets of rogue vessels. Again attention should be drawn to the heavy density of frequencies down the main lane.

Fig.8.10 Distribution of through traffic at Varne

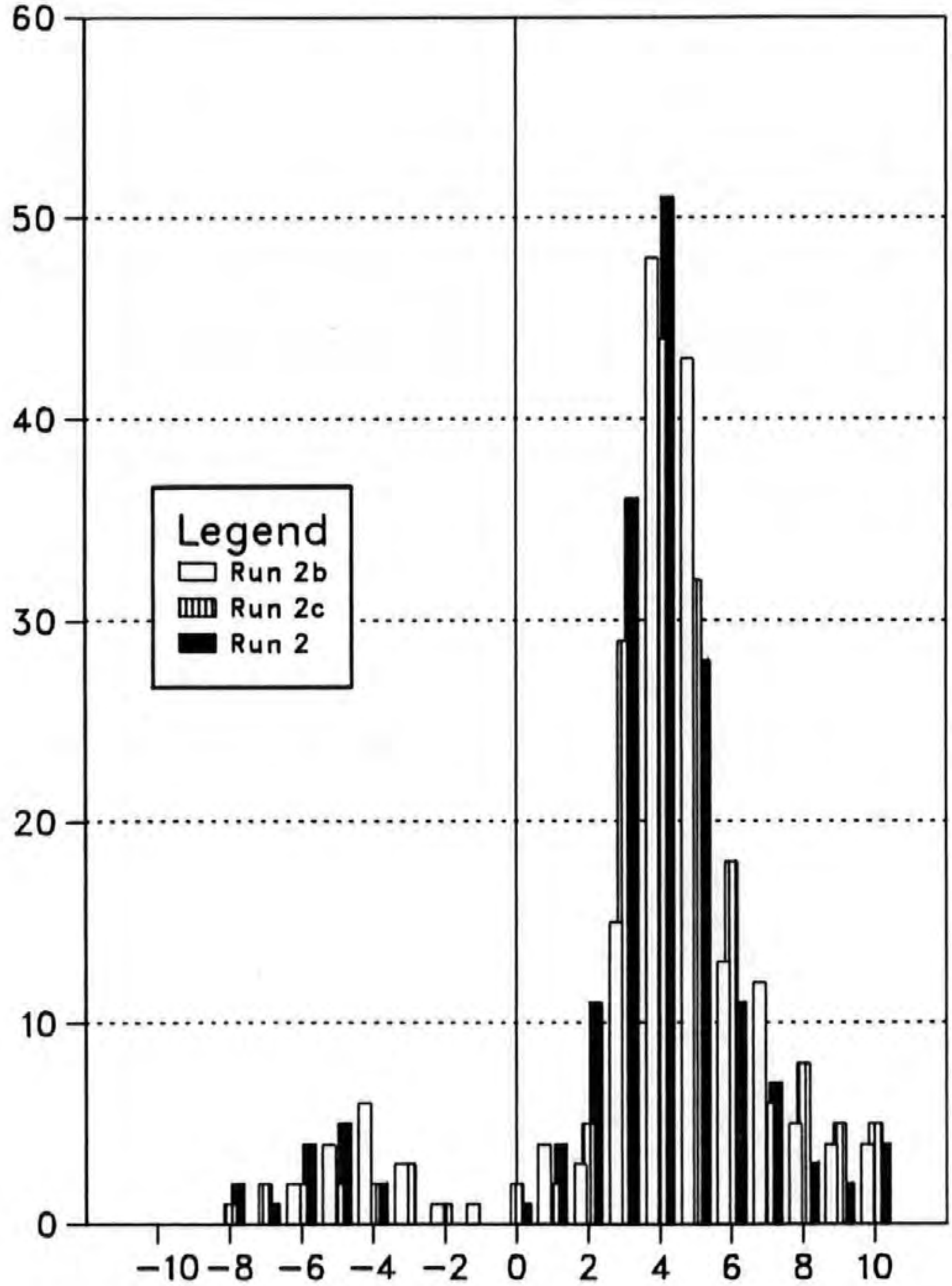


Fig.8.11 Distribution of encounters

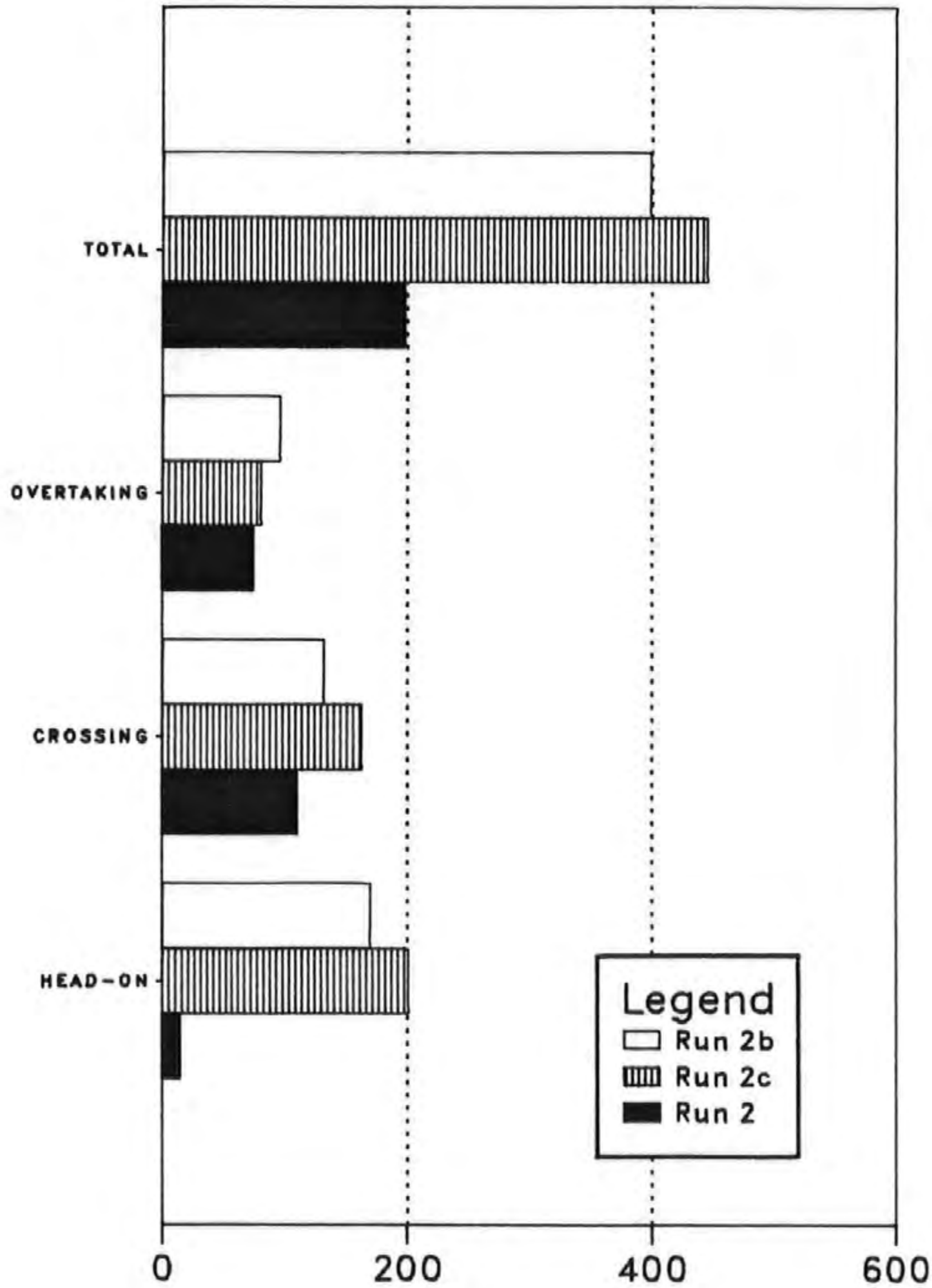


Fig.8.12a Run 2b – All encounters

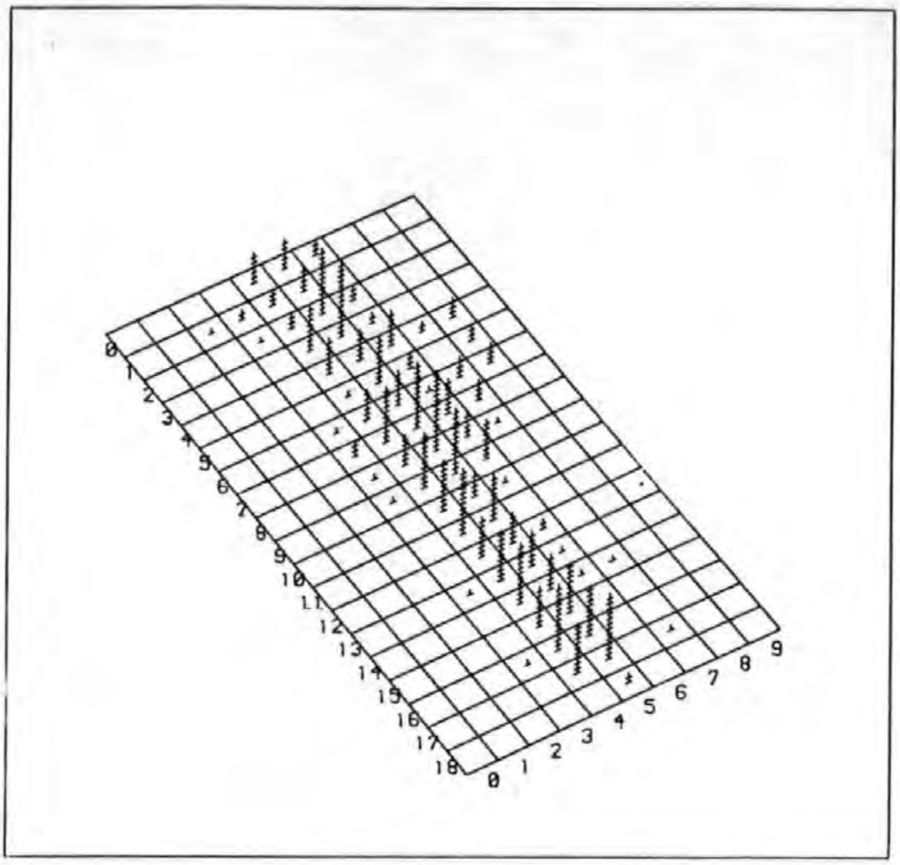


Fig.8.12b Run 2b – Head-on encounters

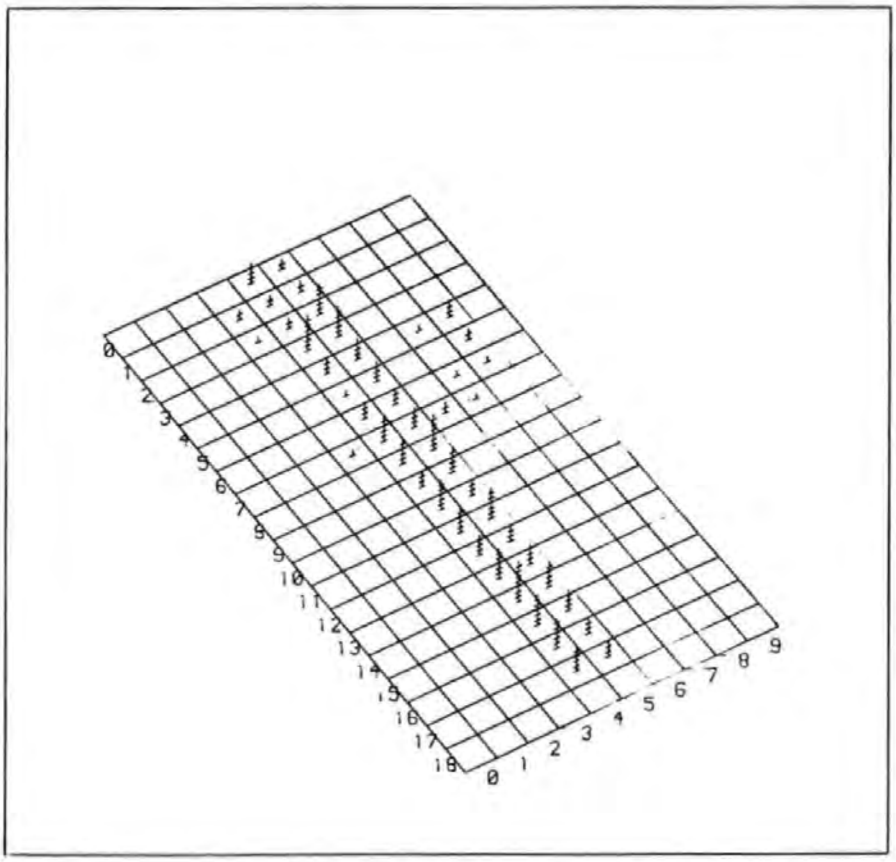


Fig.8.12c Run 2b – Crossing encounters

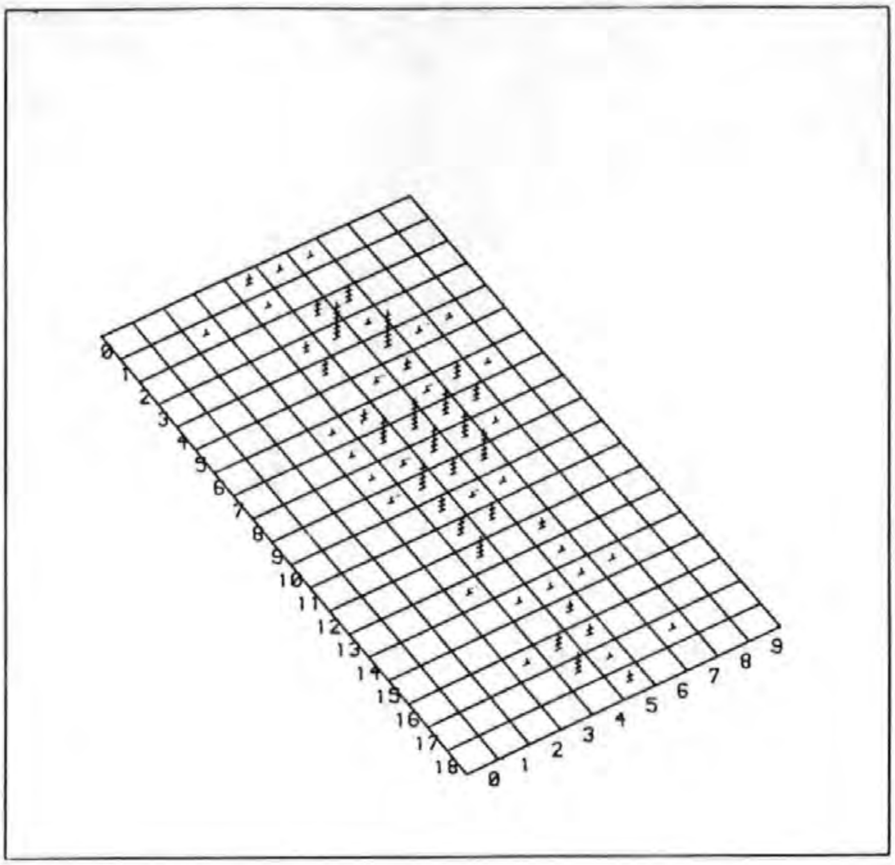


Fig.8.12d Run 2b – Overtaking encounters

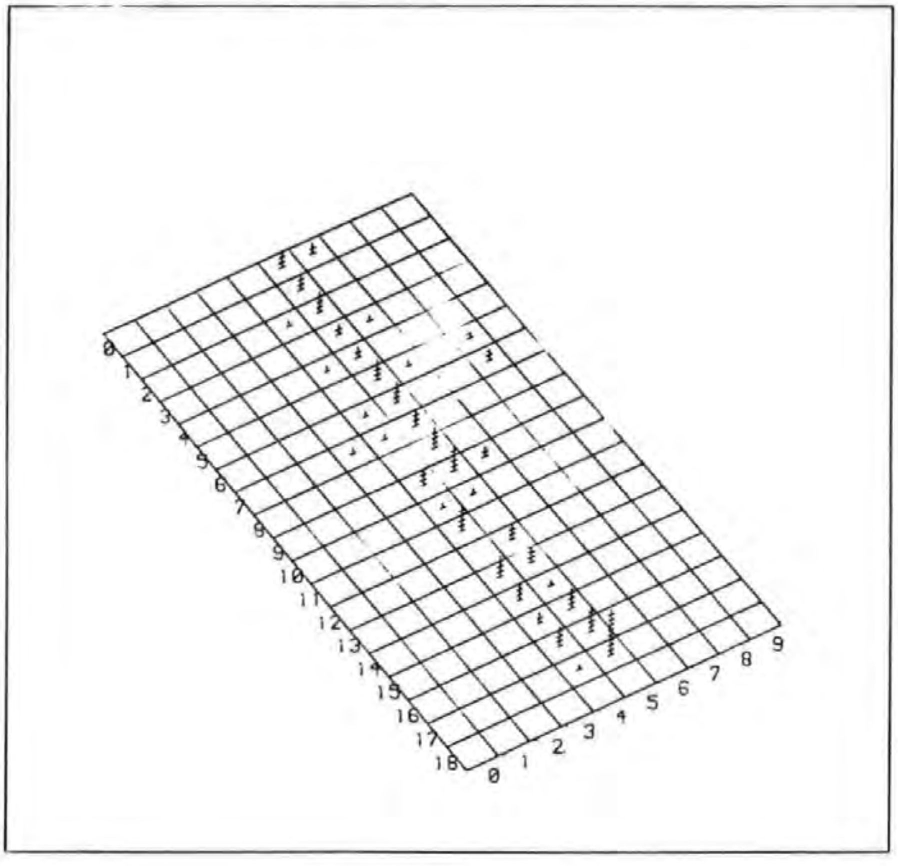


Fig.8.13a Run 2c – All encounters

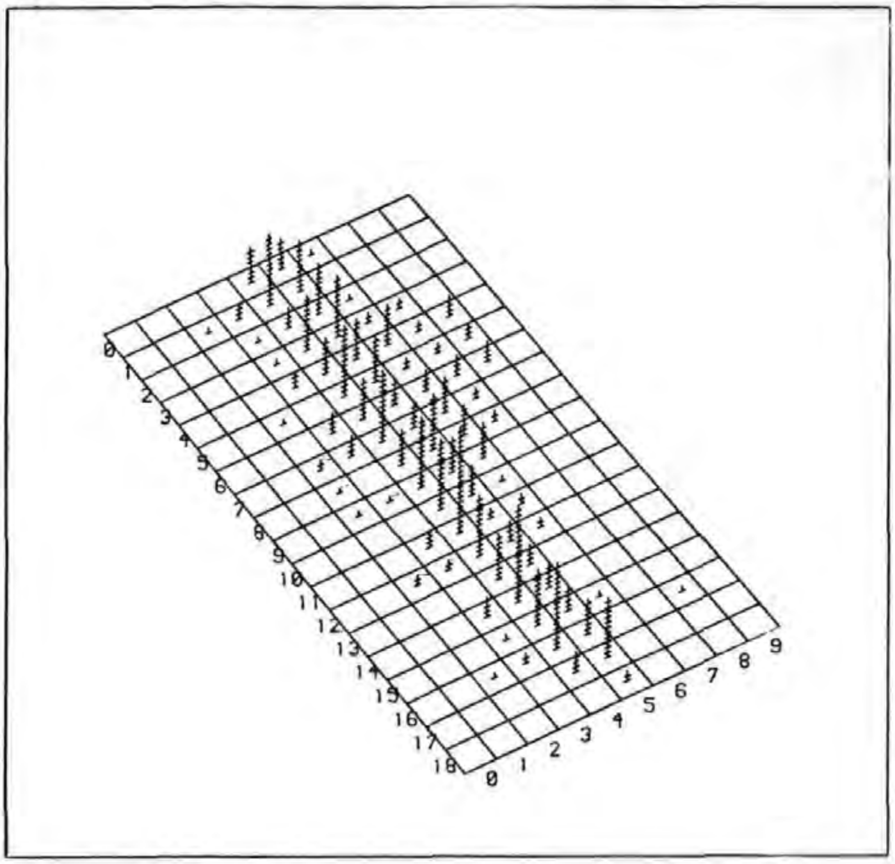


Fig.8.13b Run 2c – Head-on encounters

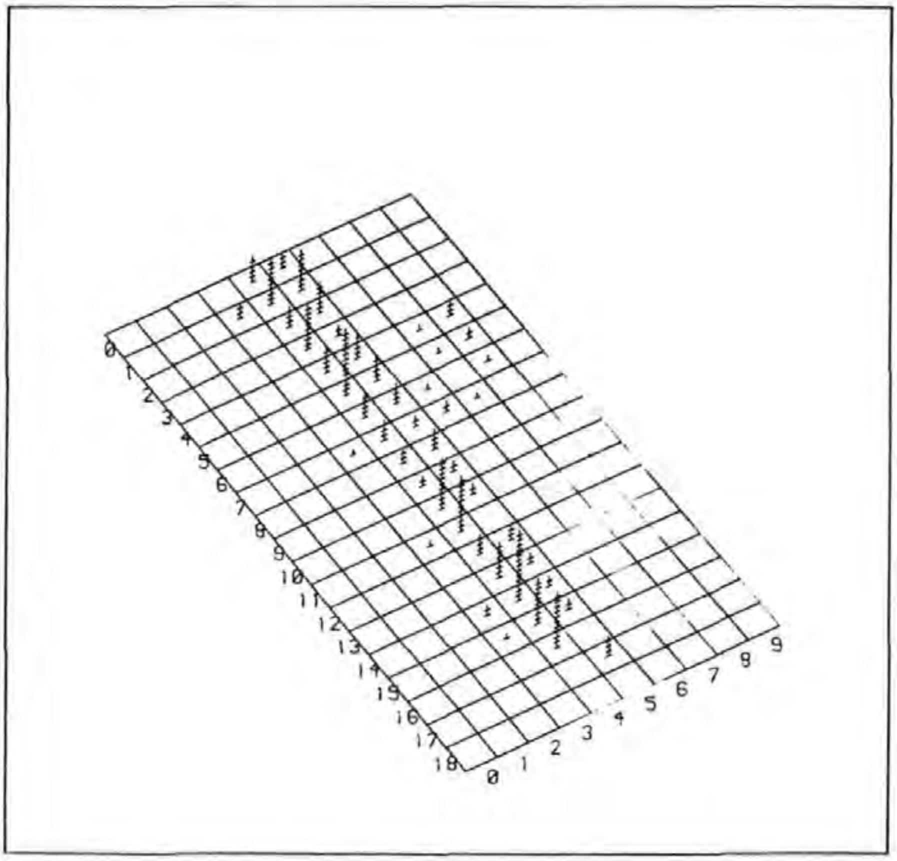


Fig.8.13c Run 2c – Crossing encounters

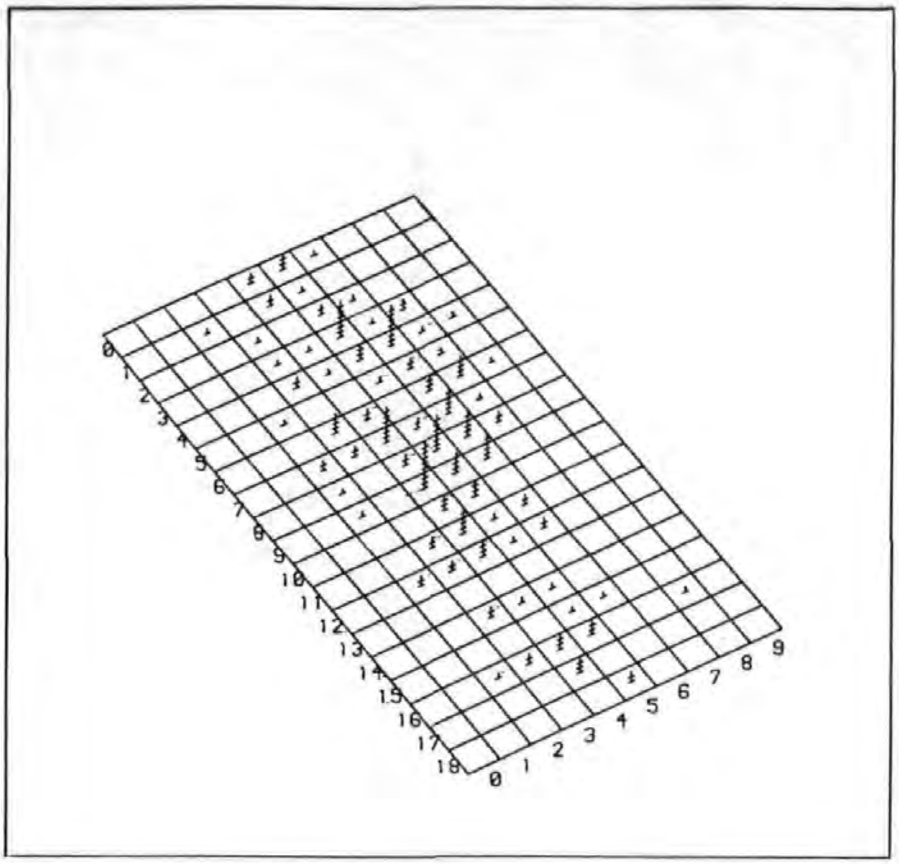


Fig.8.13d Run 2c – Overtaking encounters

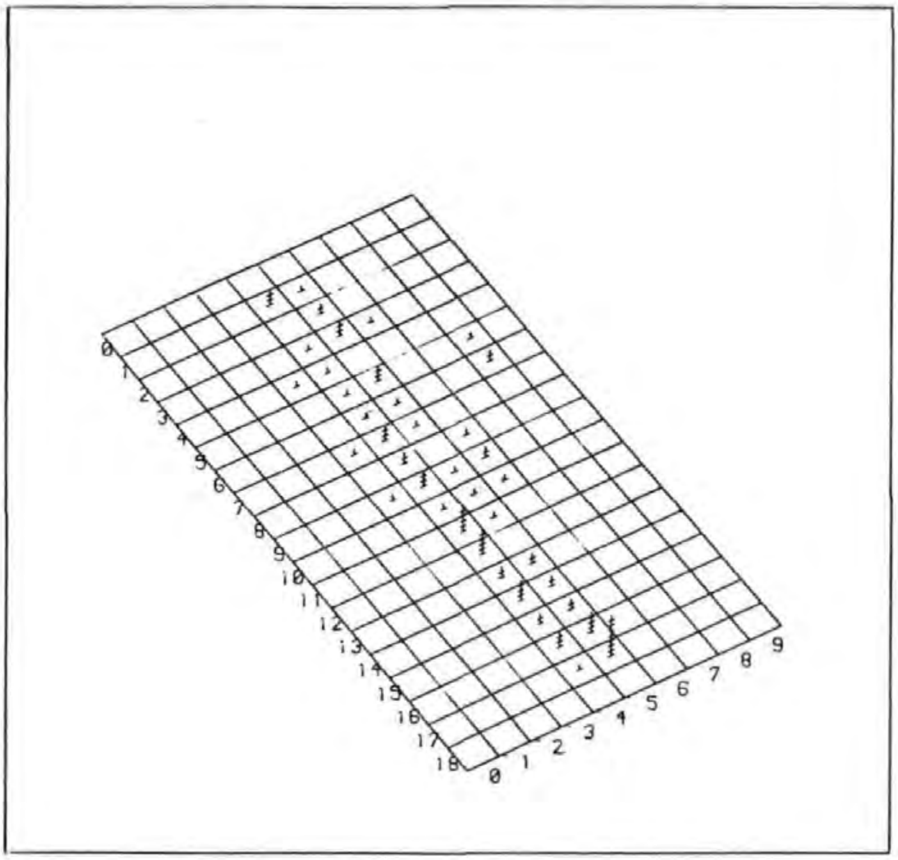


Fig.8.14 Distribution of C.P.A.s for all encounters

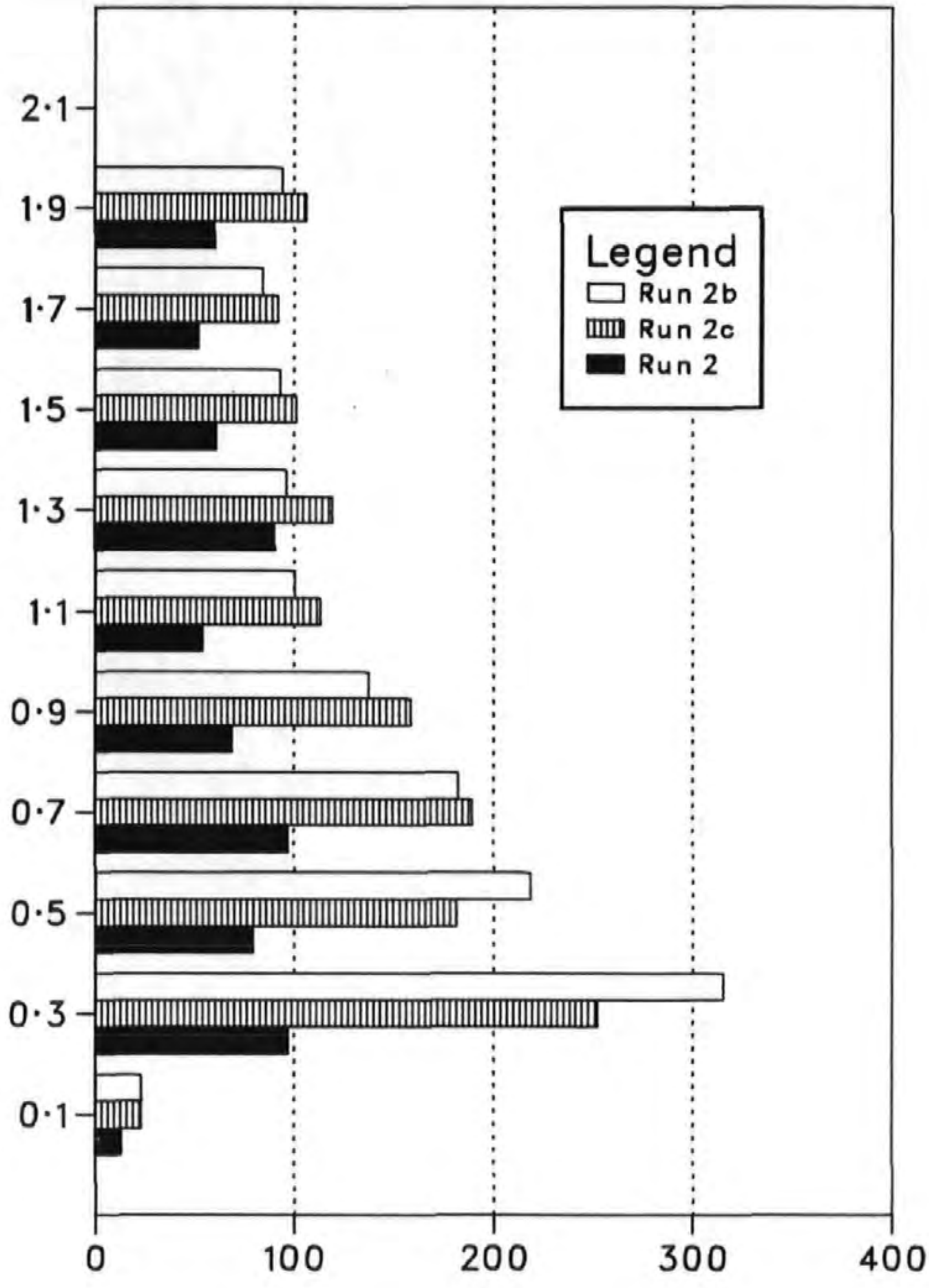


Fig.8.15 Distribution of C.P.A.s for head-on encounters

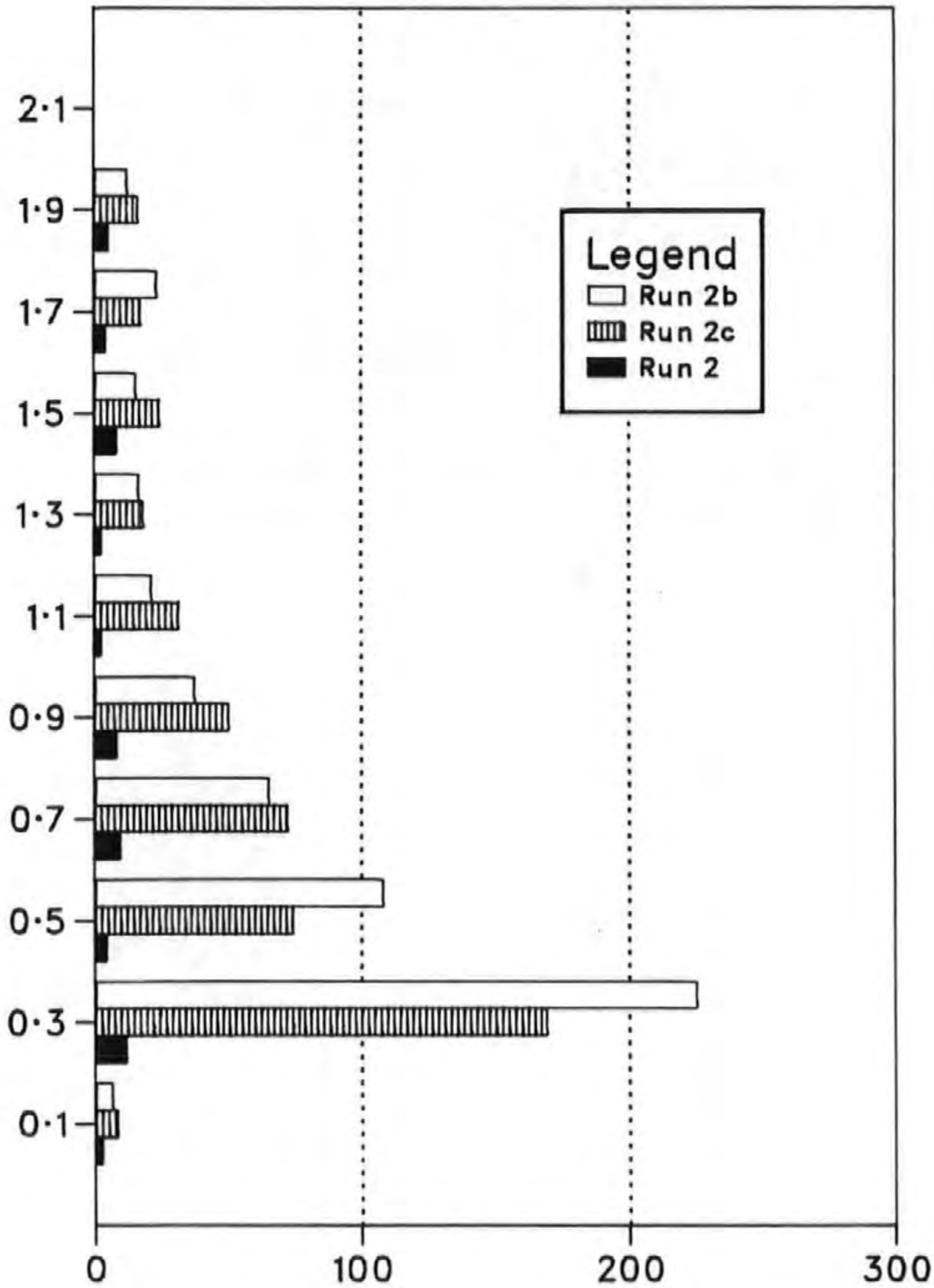


Fig.8.16 Distribution of C.P.A.s for crossing encounters

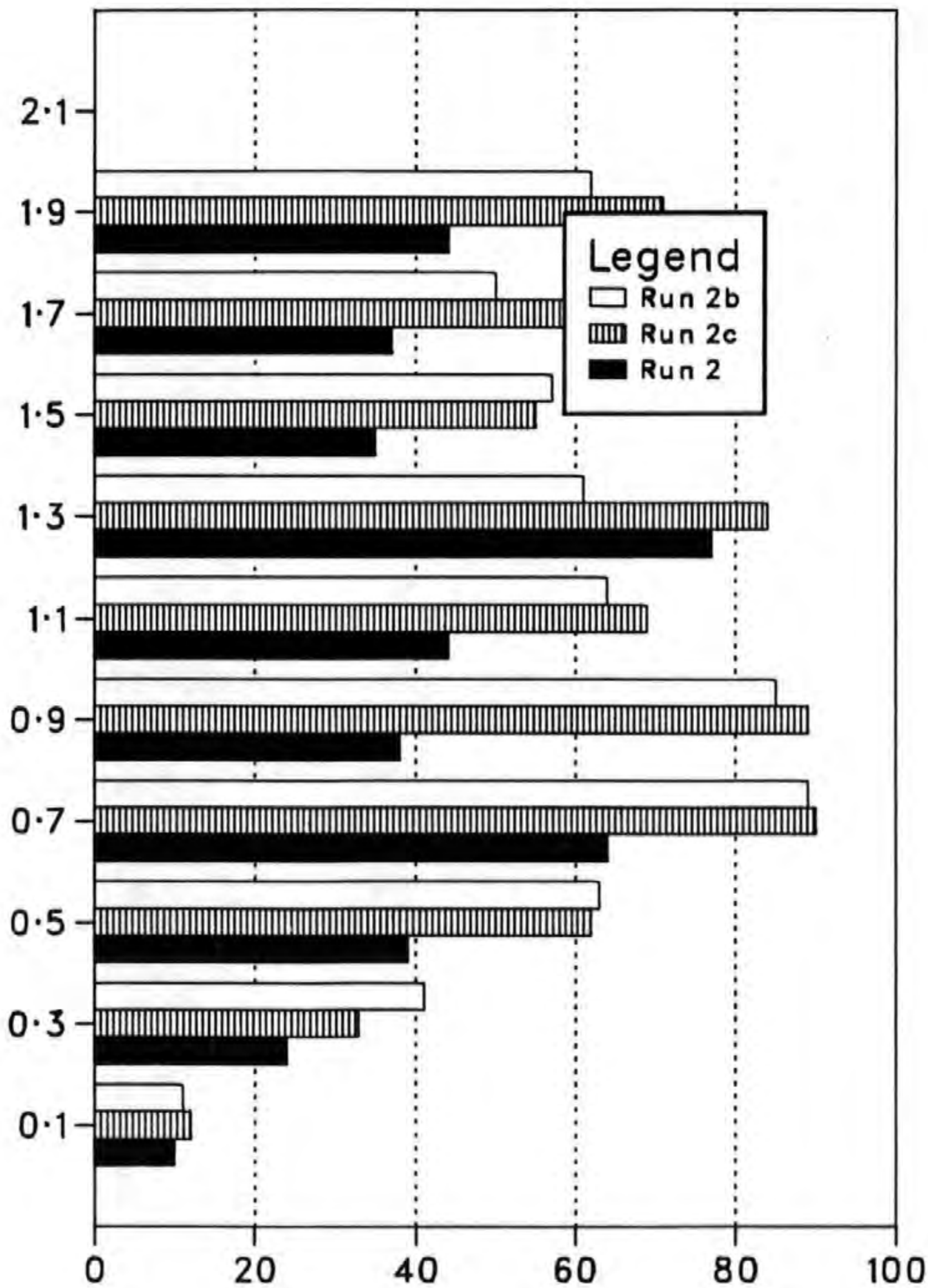


Fig.8.17 Distribution of C.P.A.s for overtaking encounters

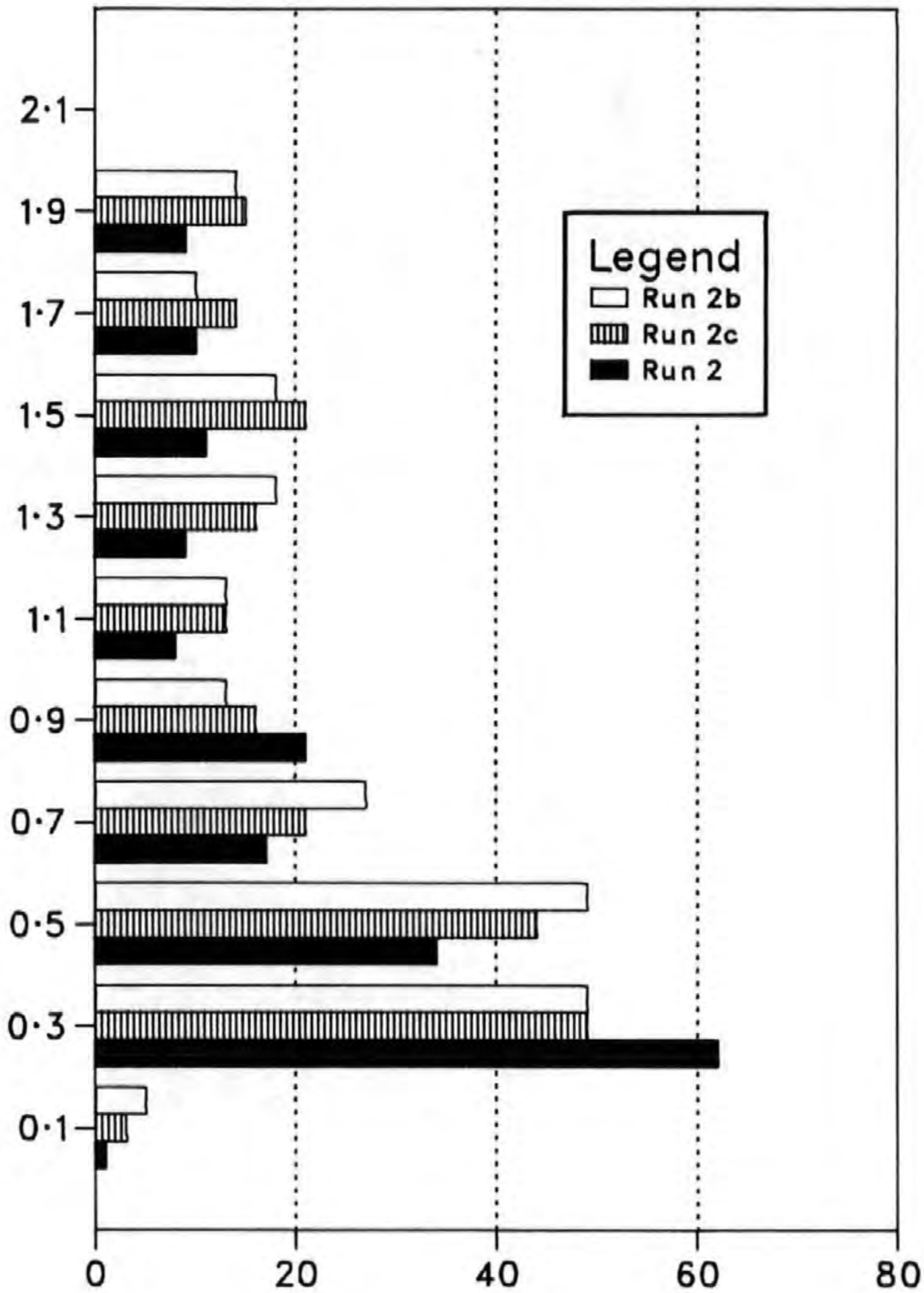


Fig.8.18a Run 2b – C.P.A.s <= 1.0

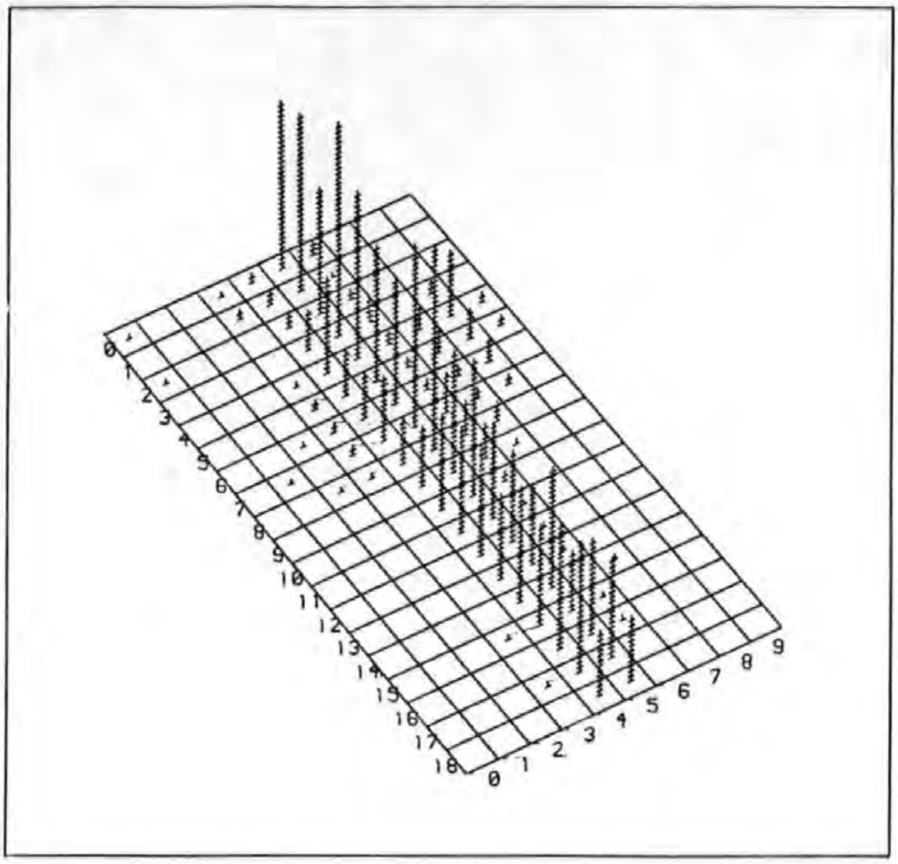


Fig.8.18b Run 2b – C.P.A.s <= 0.6

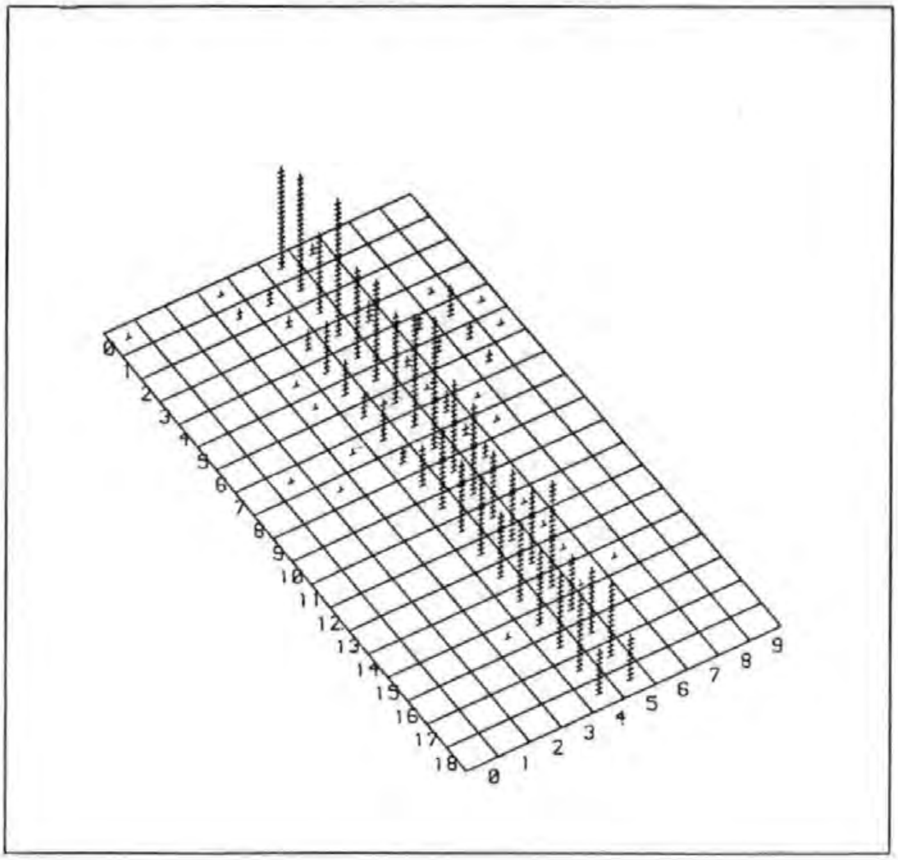


Fig.8.19a Run 2c – C.P.A.s <= 1.0

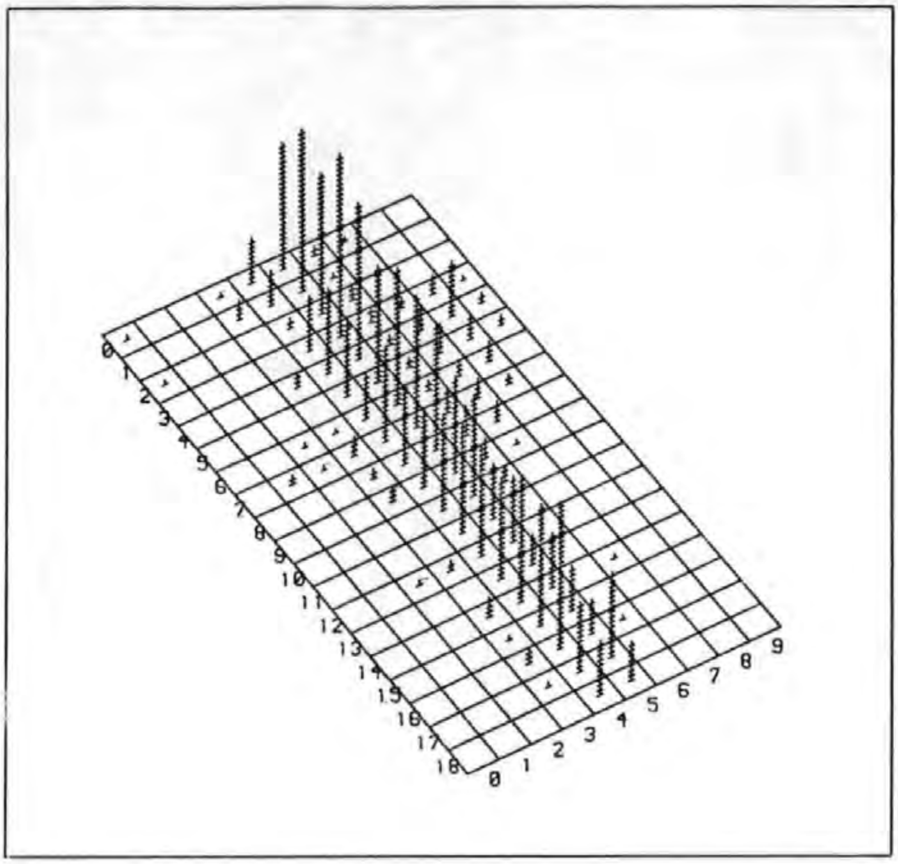
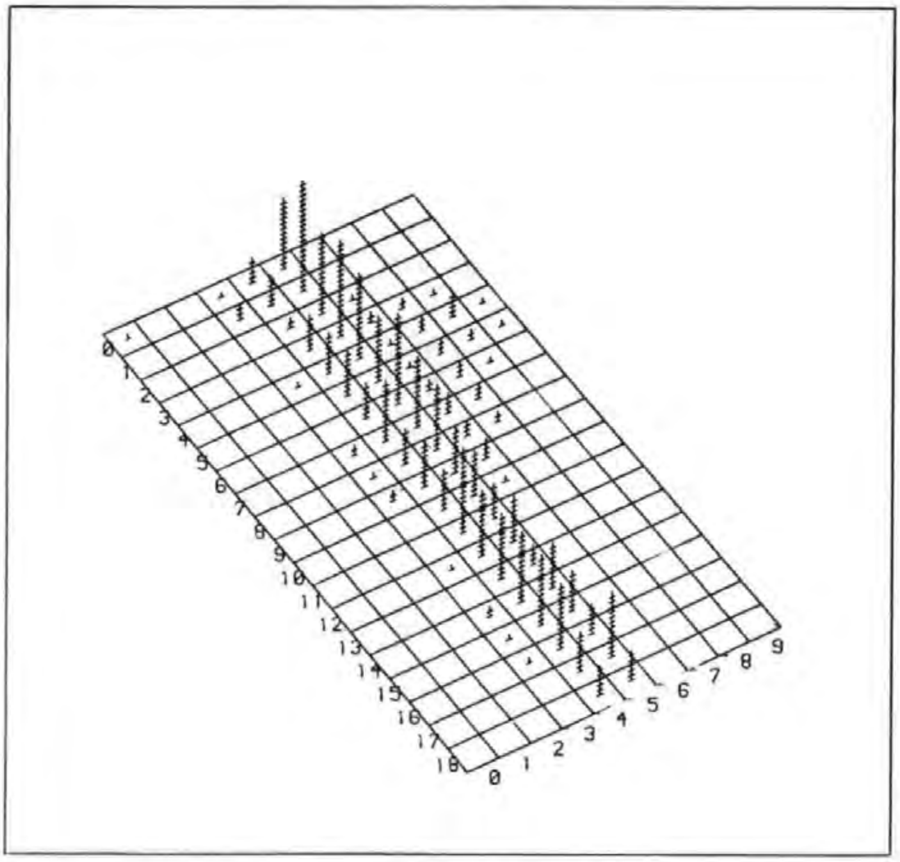


Fig.8.19b Run 2c – C.P.A.s <= 0.6



8.3 The effects of crossing rogues

8.3.1 Introduction

By definition a crossing rogue is a vessel not obeying Rule 10c whilst crossing the T.S.S.. The inclusion of Rule 10c in the Collision Regulations was designed to prevent either broad or fine crossing encounters within the T.S.S. and is a point of contention with many ferry masters as it can add several miles to a tightly scheduled crossing. Run 2d looks at the consequences of a relaxation of Rule 10c by allowing ferries to set a course directly to their destination.

8.3.2 The distribution of through vessels at the Varne

It can be seen from Figure 8.20 that there was little difference between Run 2 and Run 2d for vessels passing north of the Varne, with a mean passing distance of 1.26 n.miles for Run 2d as against 1.19 for Run 2. Whilst for those passing south of the Varne there was a significant widening of the distribution with a standard deviation of 0.6 n.miles for Run 2d and 0.3 n.miles for Run 2.

8.3.3 The distribution of the numbers of encounters

Figure 8.21 shows how the relaxing of Rule 10c resulted in an increase by 9 encounters from 198 to 207 for the total number of encounters. This was reflected almost solely in the increase in the overtaking encounters. The explanation for this was that some of the encounters that would had been crossing had now become broad overtaking encounters. Clearly any conclusions drawn from an analysis of the numbers of encounters alone was not justified, as the initial concept involved in the introduction of Rule 10c was not to reduce the total number of encounters but to reduce the fine and broad crossing encounters. It would appear then that the permitting of crossing rogues increased slightly the total number of encounters and also introduced unfavourable encounters into the system.

8.3.4 The spatial distribution of encounters

Figures 8.22a-d illustrate the spatial distribution of encounters for Run 2d. The only observation to be made is that the fan of encounters from Dover is perceptibly wider than in that for Run 2.

8.3.4 The distributions of the number of C.P.A.s

Figures 8.23 to 8.26 show how the C.P.A.s were distributed for each type of encounter situation. It can be seen (Fig. 8.23) that the total number of C.P.A.s less than 1 n.mile increased for Run 2d from 359 to 402. Figures 8.24 and 8.25 show further that this increase was due to the head-on and the crossing encounters.

8.3.6 The spatial distribution of C.P.A.s

The distribution of C.P.A.s less than 1.0 n.miles and less than 0.6 n.miles are shown in Figure 8.27a-b. The only notable result to be drawn was that the C.P.A.s less than or equal to 1.0 n.miles seemed to be more widely spread across the grid.

Fig.8.20 Distribution of through traffic at Varne

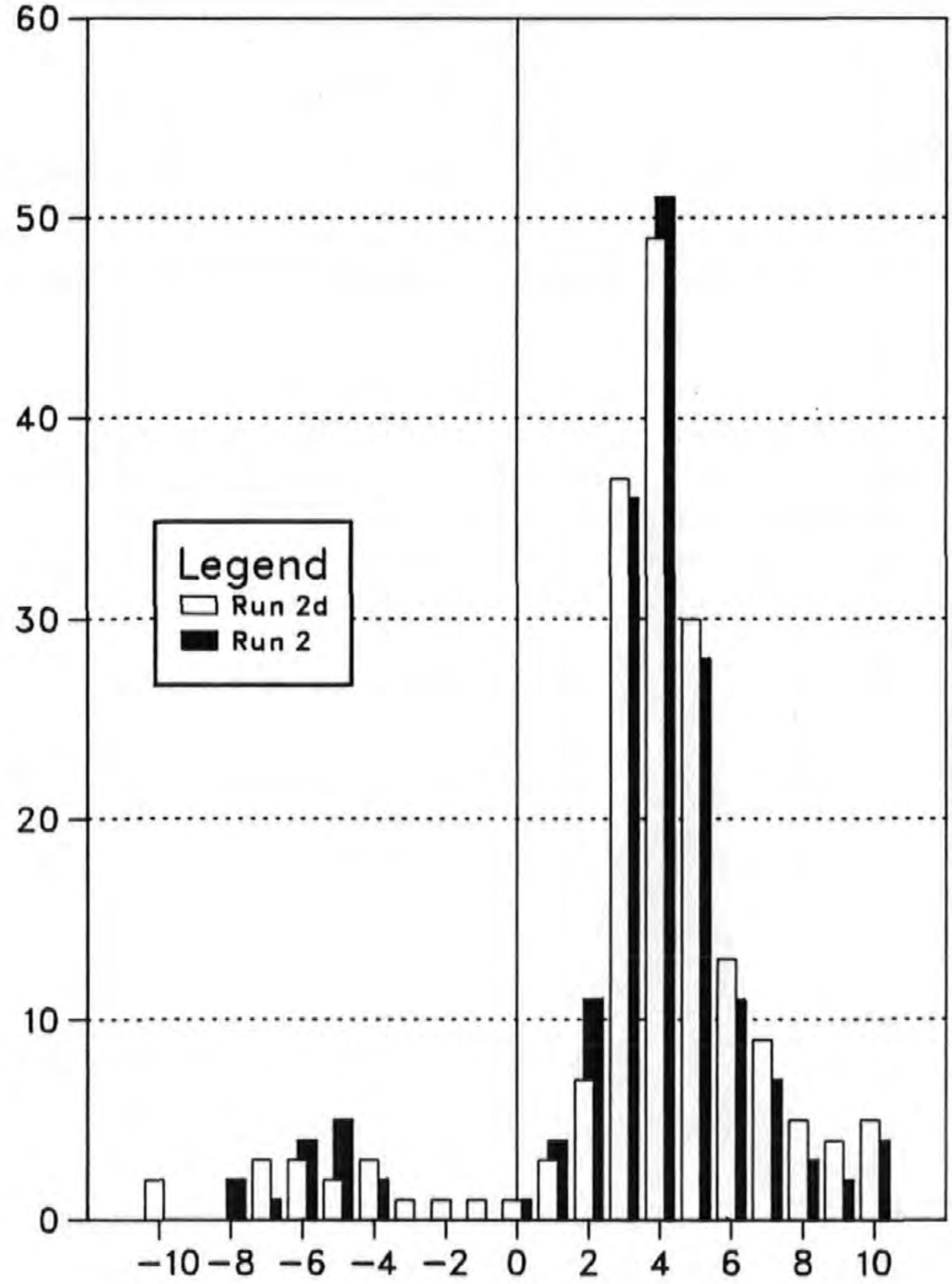


Fig.8.21 Distribution of encounters

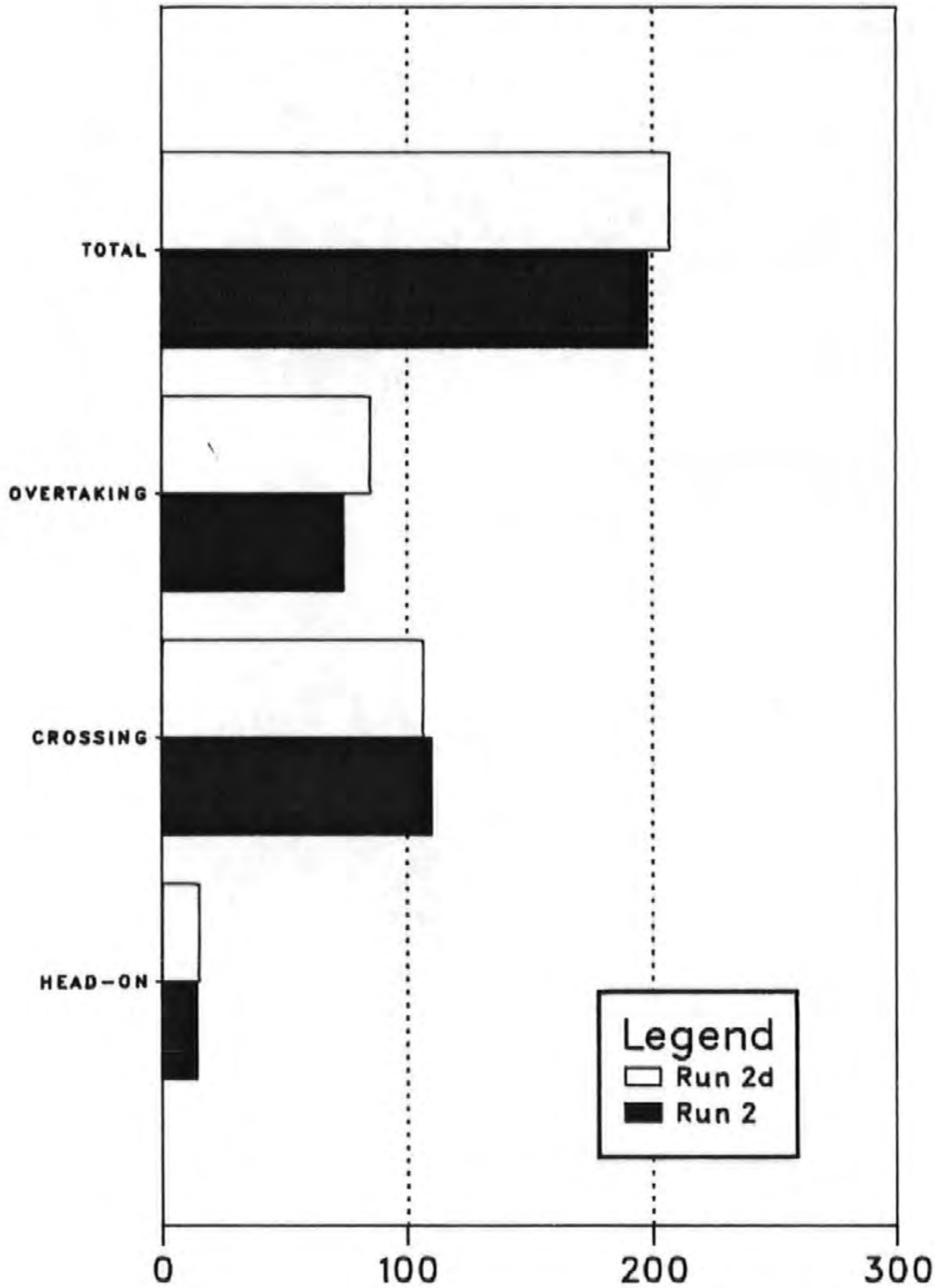


Fig.8.22a Run 2d – All encounters

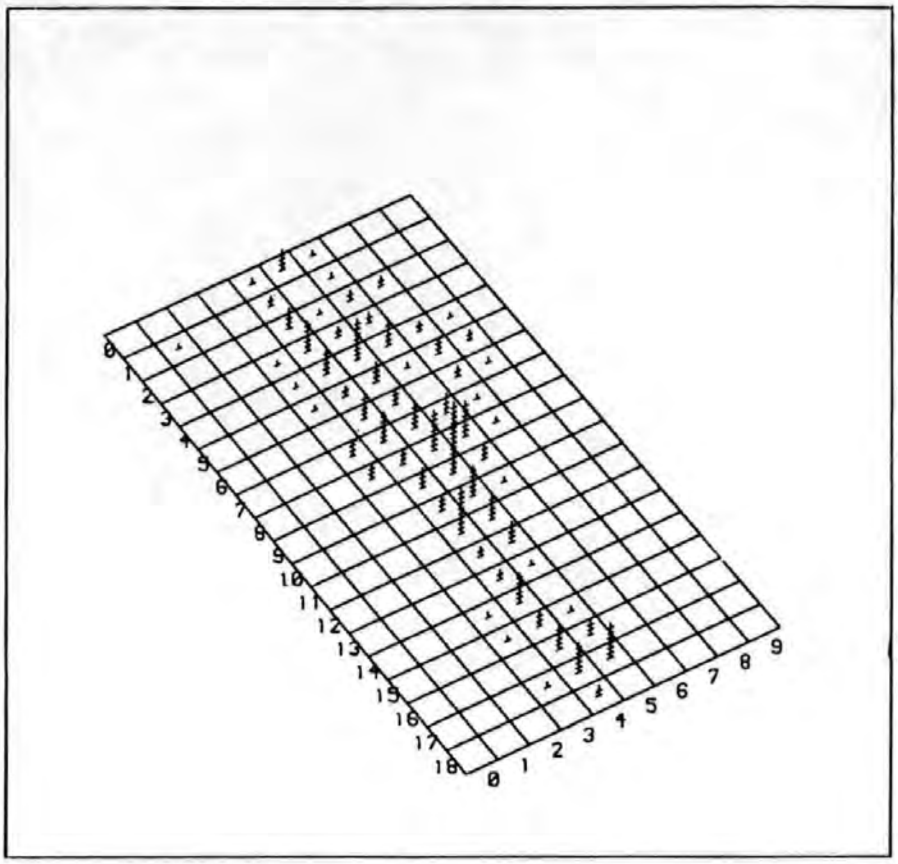


Fig.8.22b Run 2d – Head-on encounters

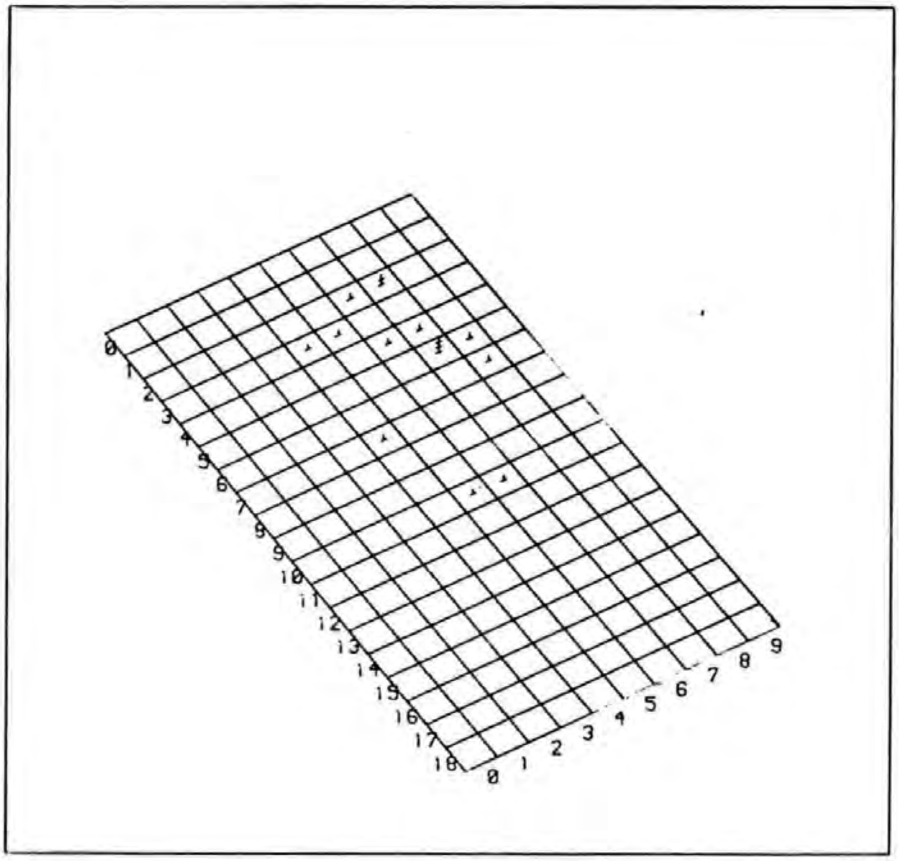


Fig.8.22c Run 2d – Crossing encounters

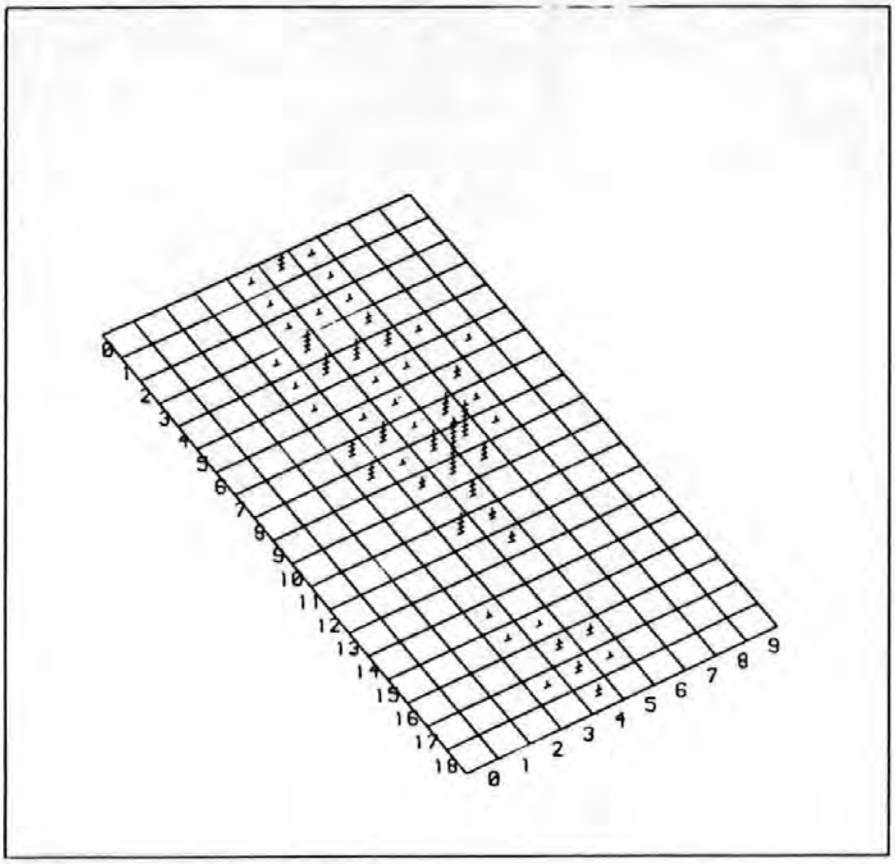


Fig.8.22d Run 2d – Overtaking encounters

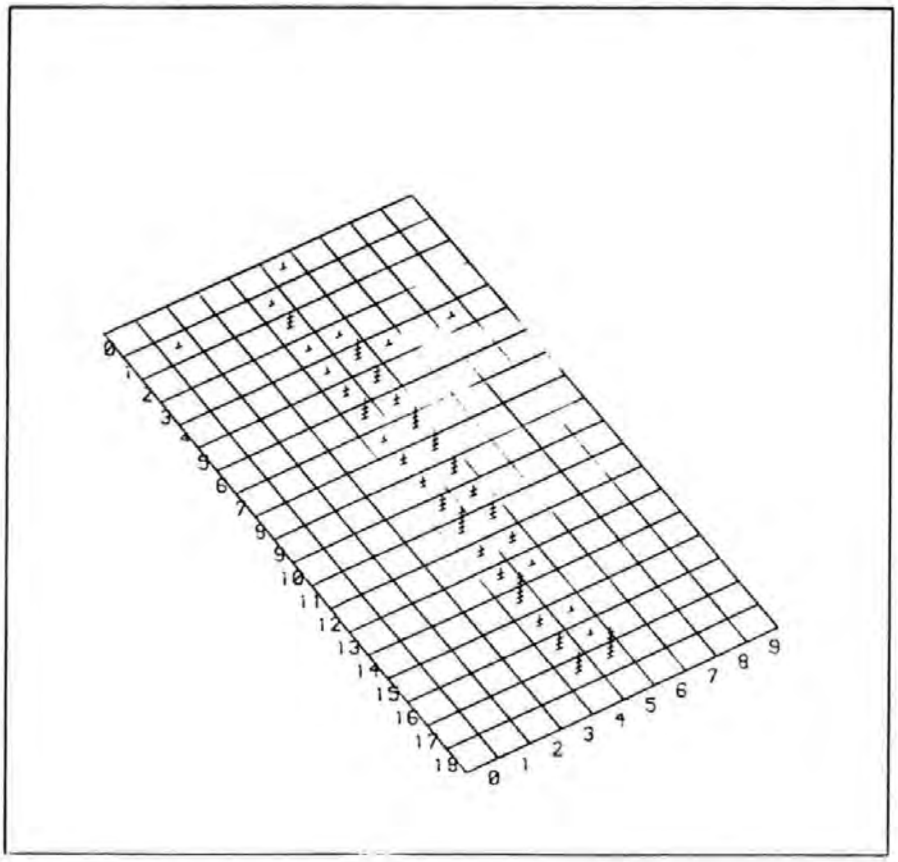


Fig.8.23 Distribution of C.P.A.s for all encounters

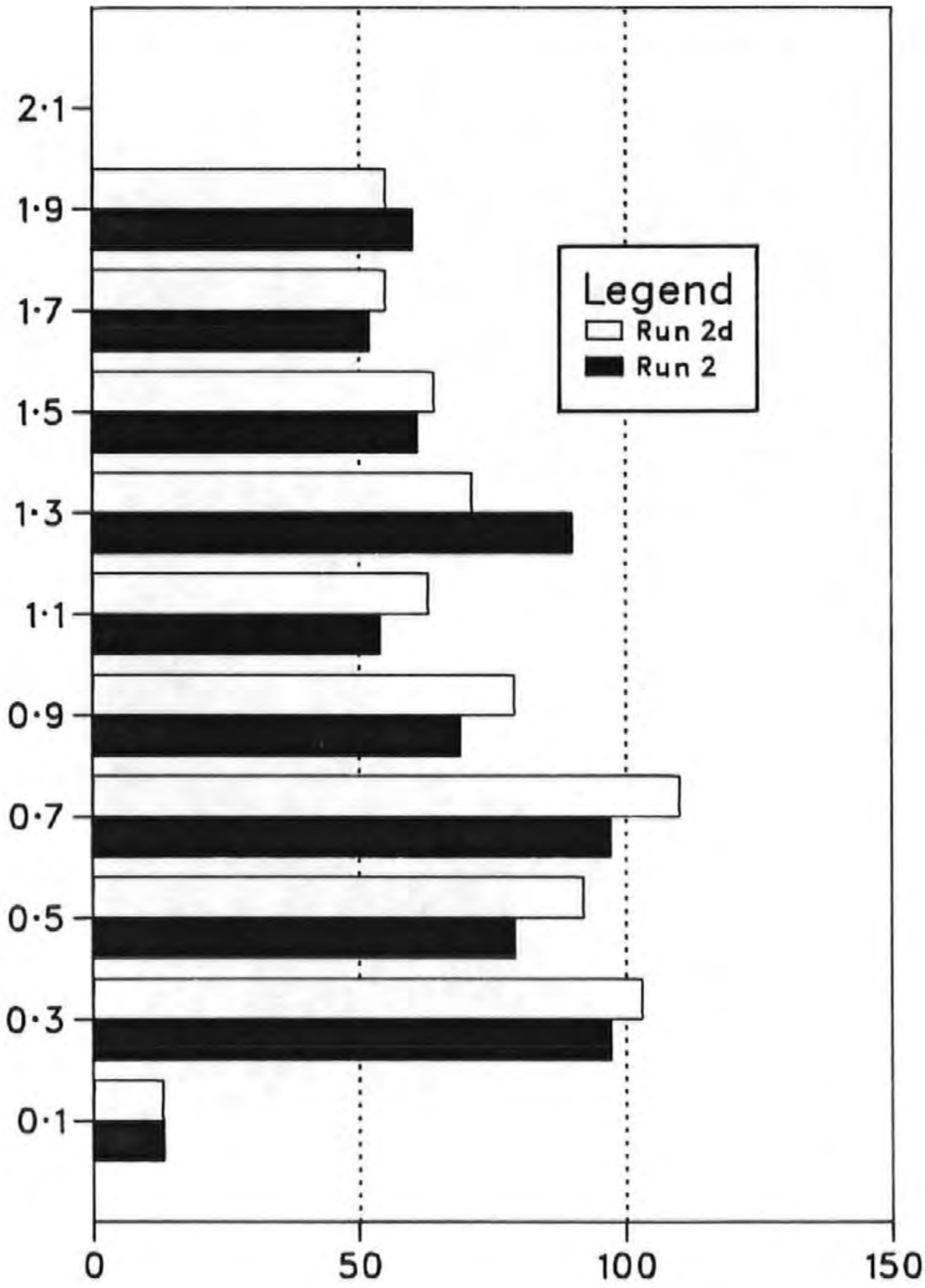


Fig.8.24 Distribution of C.P.A.s for head-on encounters

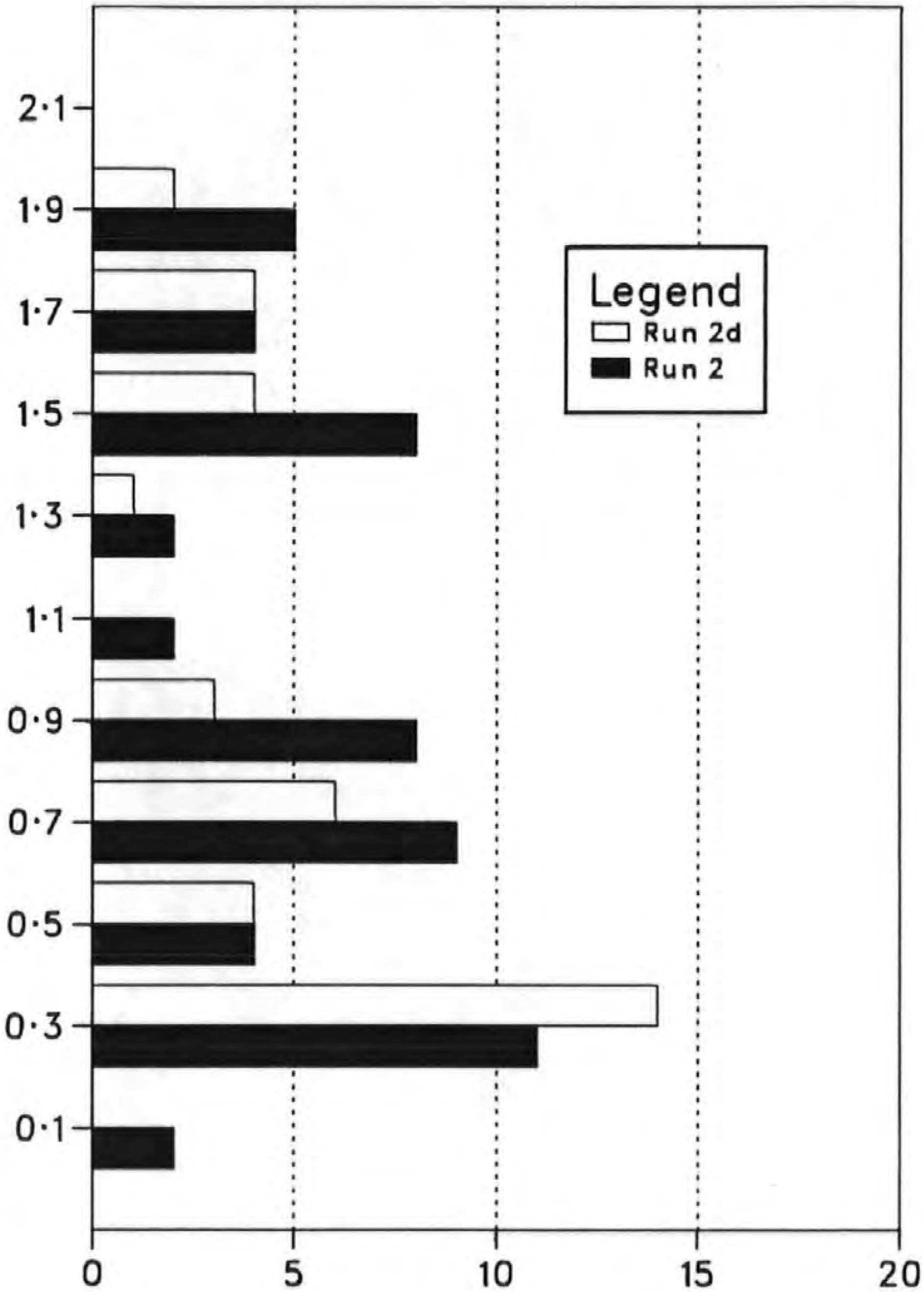


Fig.8.25 Distribution of C.P.A.s for crossing encounters

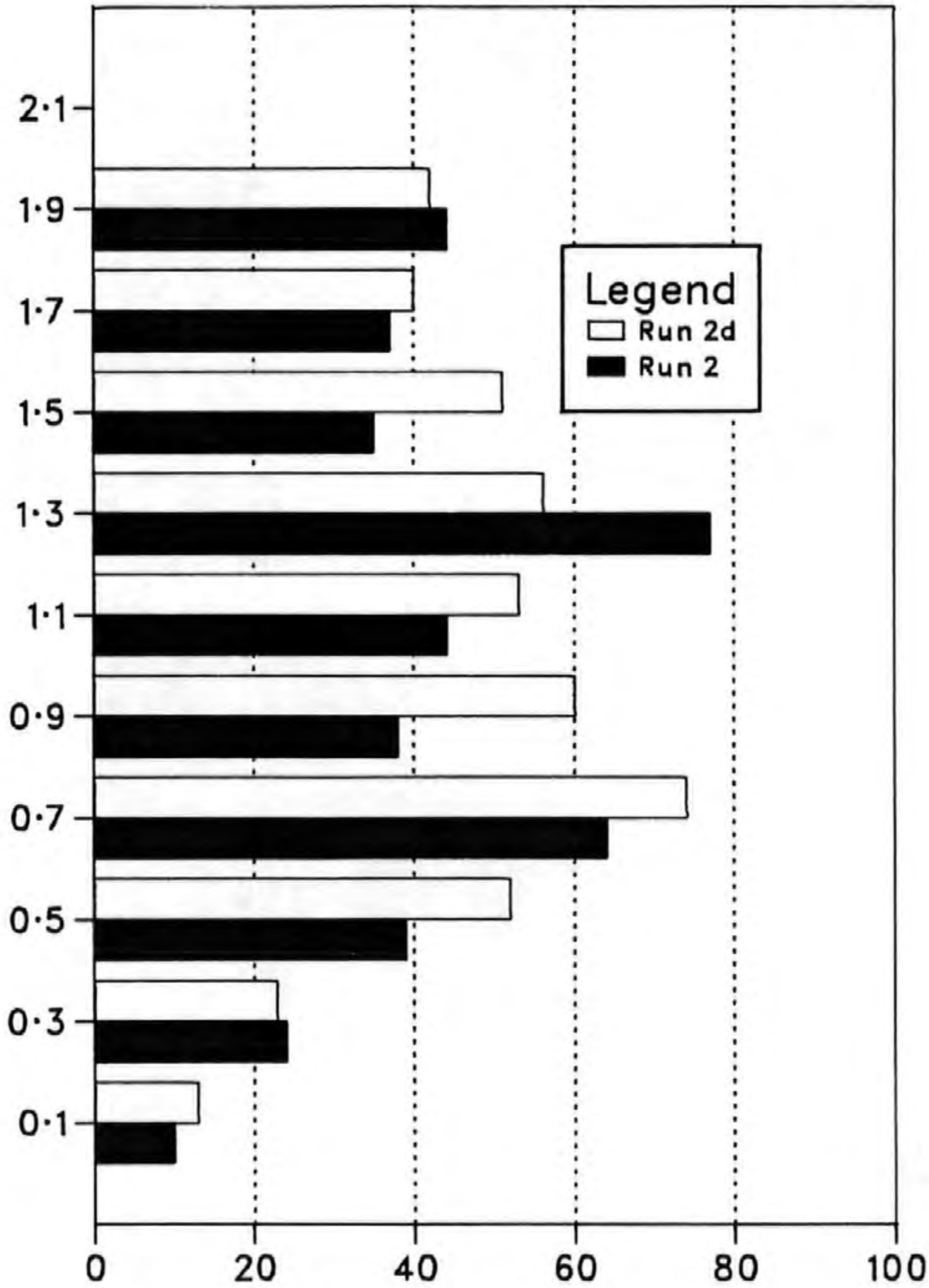


Fig.8.26 Distribution of C.P.A.s for overtaking encounters

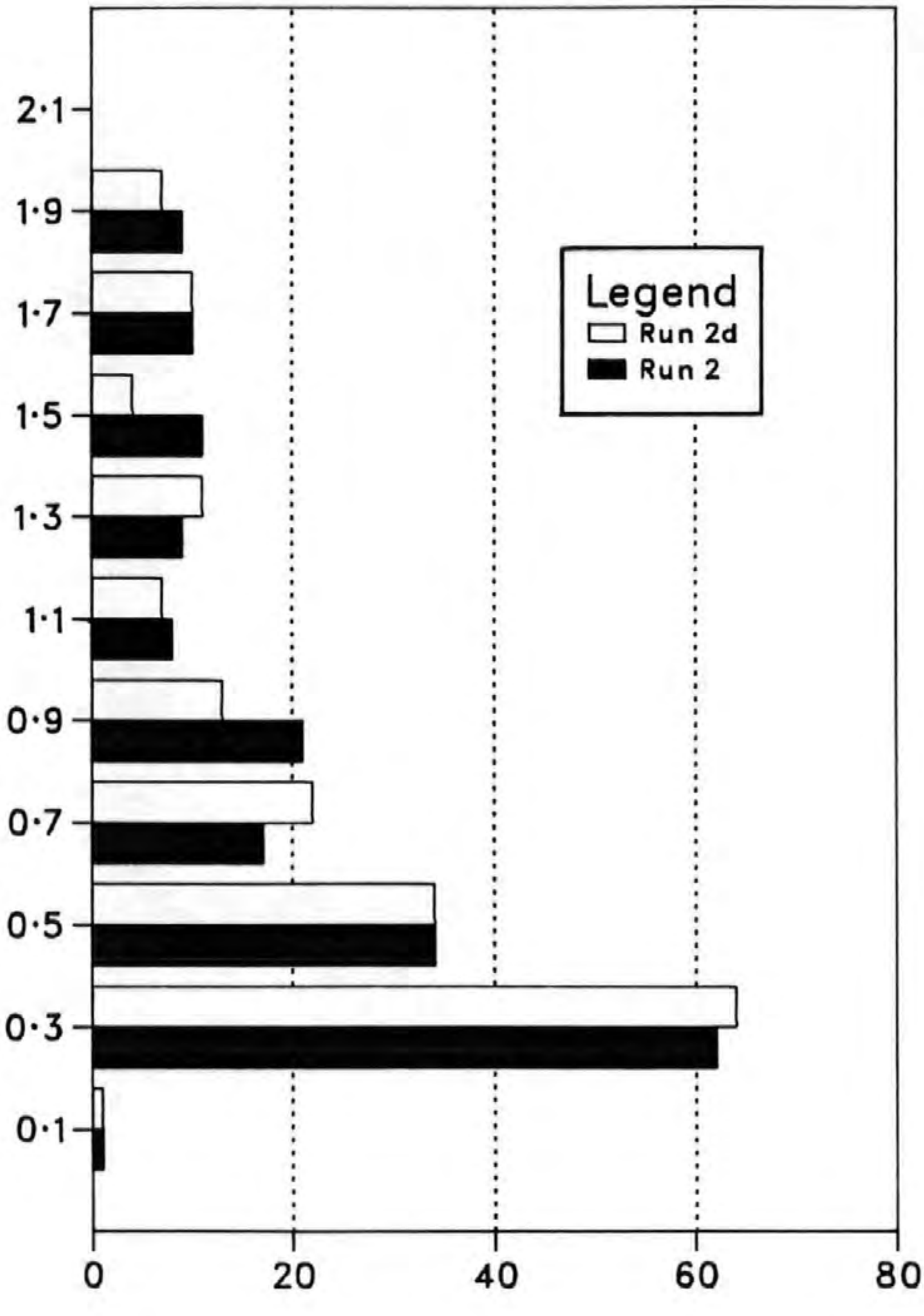


Fig.8.27a Run 2d – C.P.A.s <= 1.0

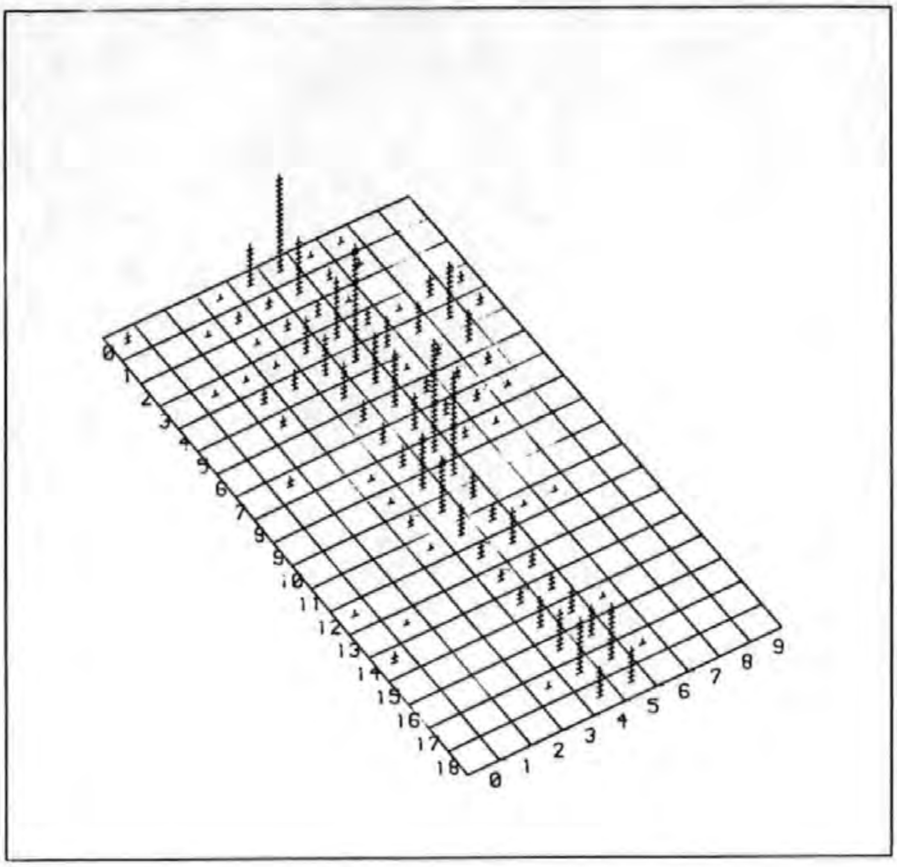
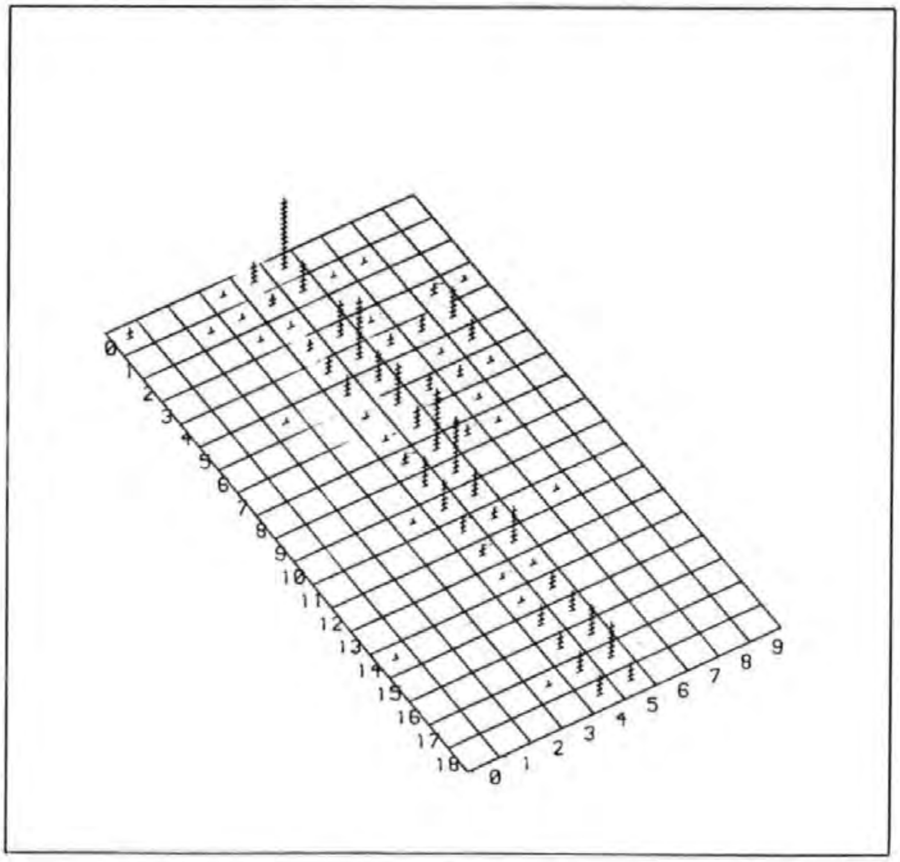


Fig.8.27b Run 2d – C.P.A.s <= 0.6



8.4 The restriction of the traffic flow

8.4.1 Introduction

It was decided that a further use of the model might be to attempt to predict the effect of restricting the flow of traffic by the introduction of an obstruction to the traffic flow. The obstruction was introduced as a stationary buoy with a domain to all traffic of 0.8 n.miles and was placed at the grid position (4.1,5.5) This obstruction could in practice be an oil-rig, a wreckage of a U.L.C.C. or even an oil slick.

8.4.2 The distribution of through traffic at the Varne

Figure 8.28 shows the effect of the obstruction on the through traffic. It can be seen that only 77% passed north of the Varne as opposed to the 90% under normal circumstances. Approximately 67% of the through traffic passed north of the obstruction.

8.4.3 The distribution of the number of encounters

Figure 8.29 shows how the total number of encounters increased from 198 to 253, with the main increase being in the number of overtaking encounters from 74 to 104. In this situation the number of encounters was not the best measure of the disruptive effect of the obstruction on the shipping system because of the condition imposed on the collision avoidance algorithm that a vessel can only consider one encounter at a time. An encounter was recognized if and only if a vessel had to alter course for another and as such any simultaneously occurring encounters were lost. Such occurrences were likely to be frequent in this particular run and for that reason it was more reasonable to consider the distribution of C.P.A.s.

8.4.4 The spatial distribution of encounters

Figures 8.30a-d show the spatial distributions of encounters and the gap left after vessels had manoeuvred around the obstruction can easily be identified.

8.4.5 The distribution of C.P.A.s

Figures 8.31 to 8.34 show how the effect of the obstruction was to increase the number of close encounters, in particular the number of approaches less than or equal to two cables. The total number of C.P.A.s less than 2 n.miles increased from 359 to 403. Figures 8.32 to 8.34 show that the increases where not isolated to any particular encounter type but were spread over all three types.

8.4.6 The spatial distribution of C.P.A.s

Figures 8.35a-b show more clearly how vessels were forced to manoeuvre around the obstruction. It was noticable how the frequencies increased in the immediate vicinity of the obstruction.

Fig.8.28 Distribution of through traffic at Varne

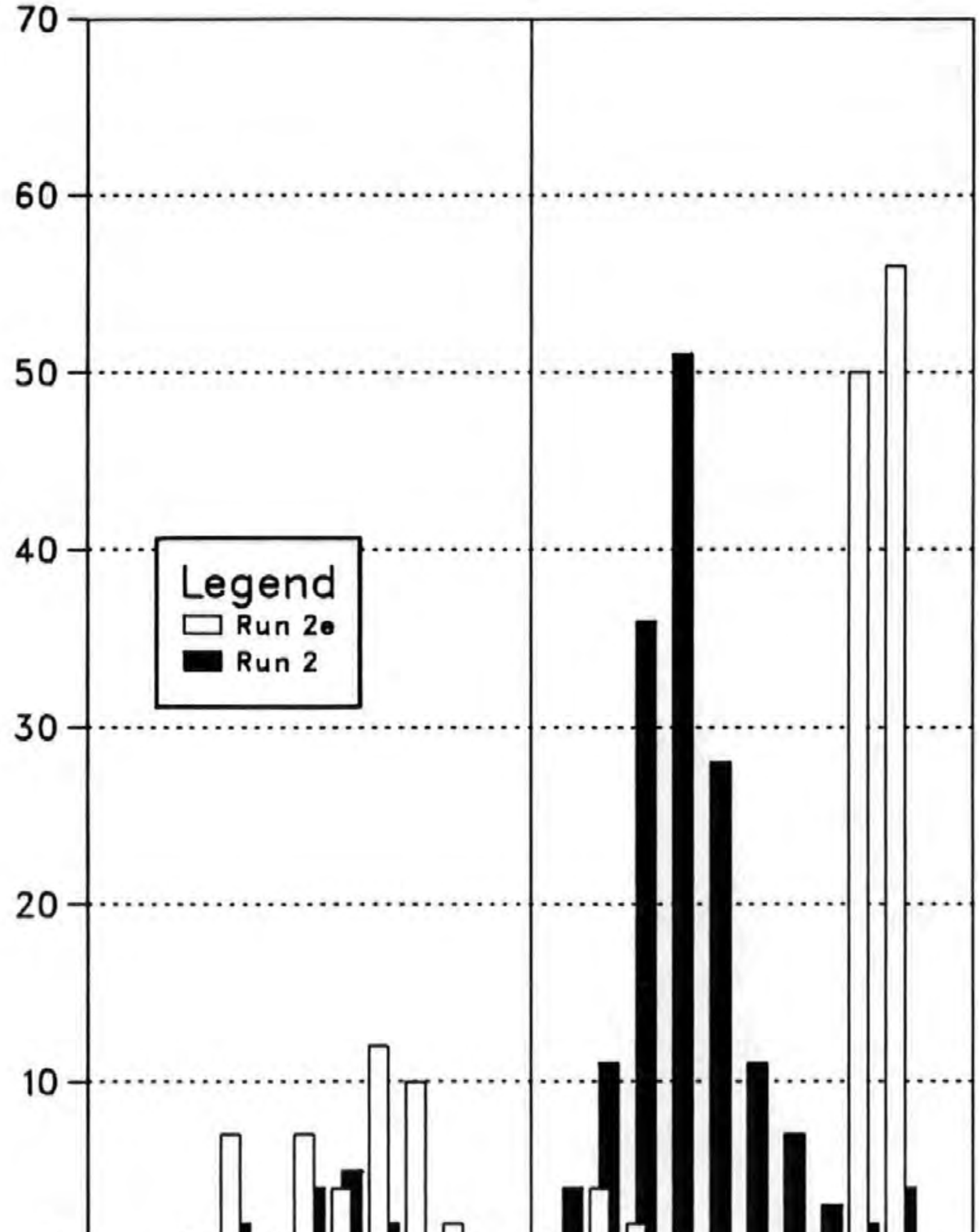


Fig.8.29 Distribution of encounters

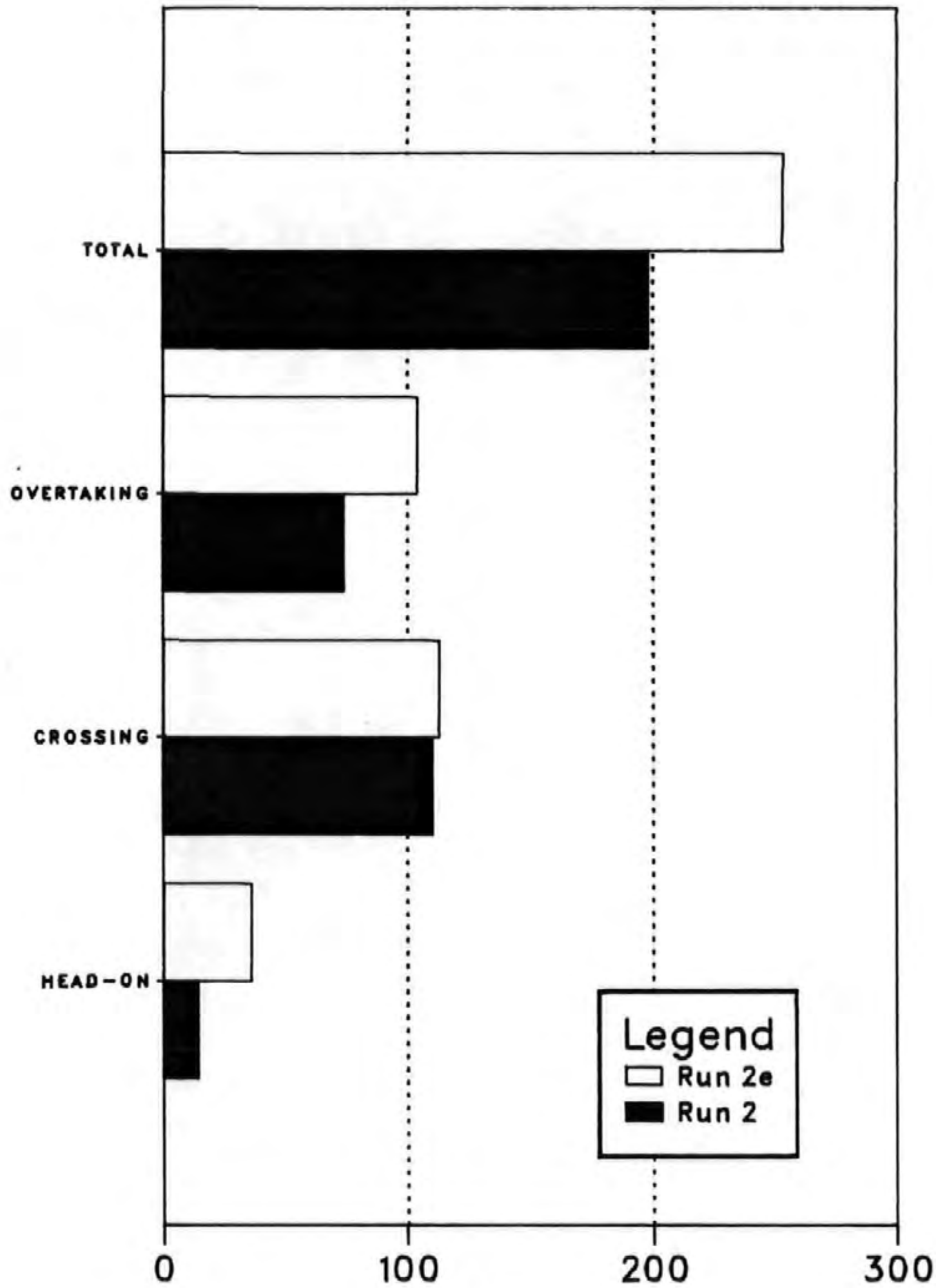


Fig.8.30a Run 2e – All encounters

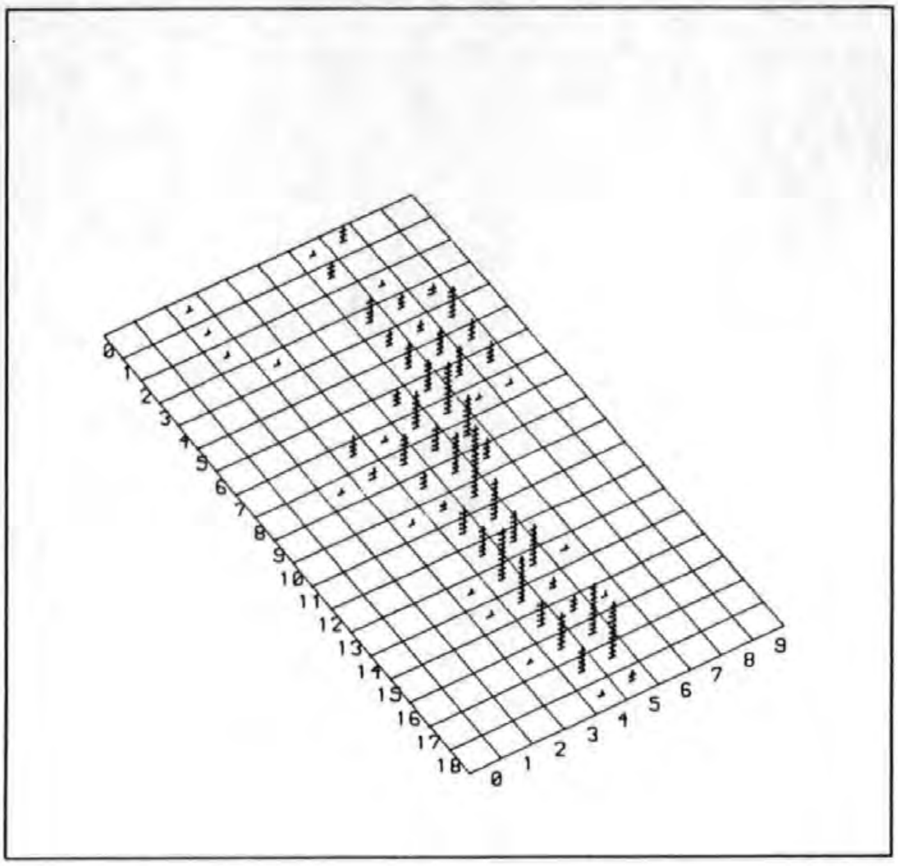


Fig.8.30b Run 2e – Head-on encounters

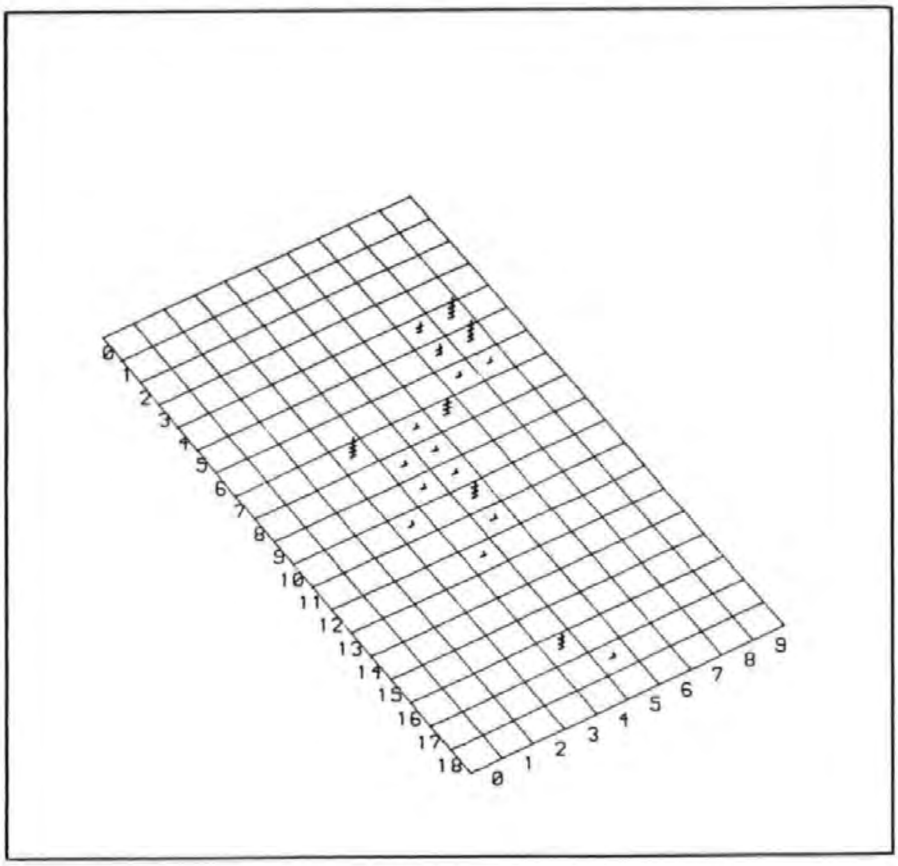


Fig.8.30c Run 2e – Crossing encounters

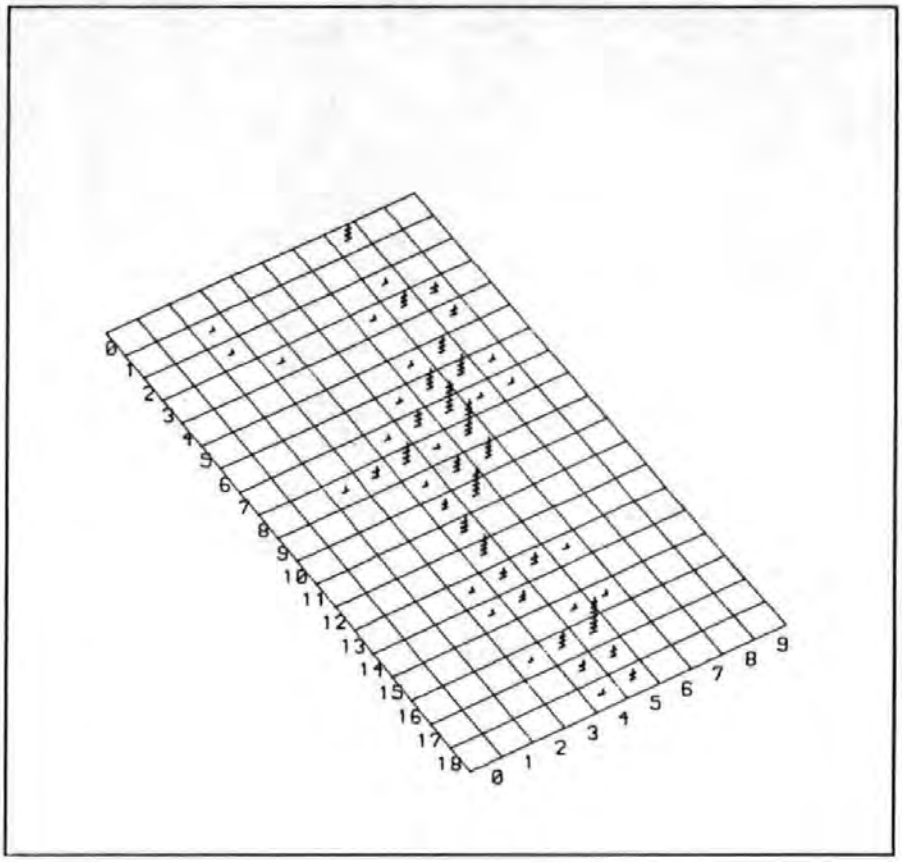


Fig.8.30d Run 2e – Overtaking encounters

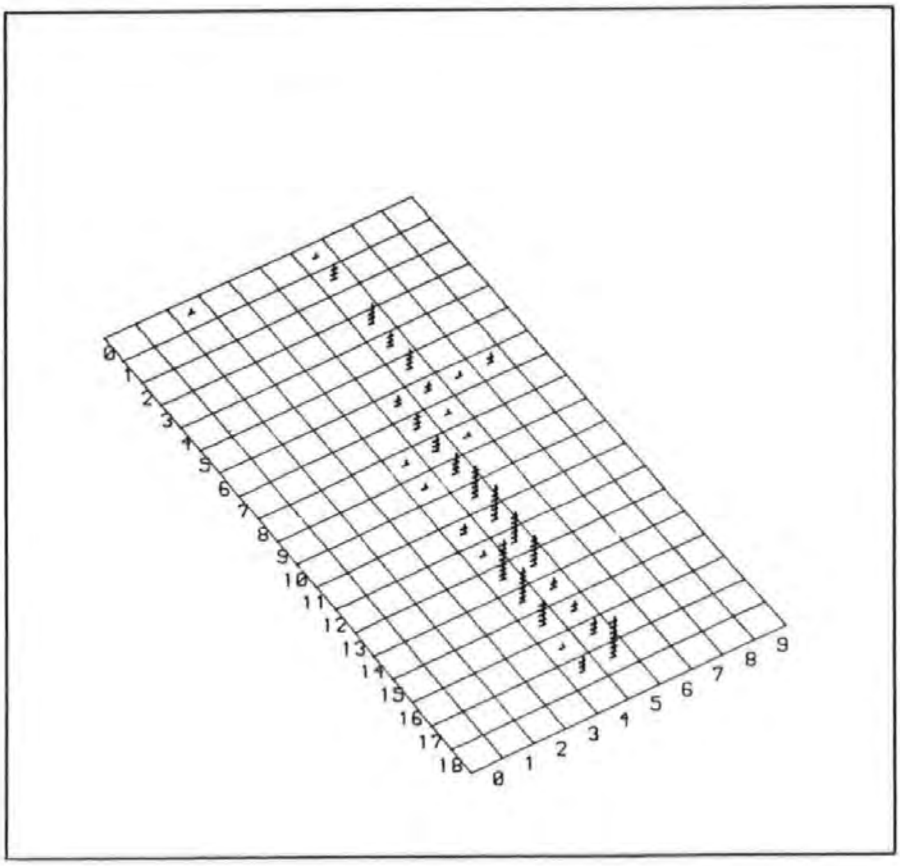


Fig.8.31 Distribution of C.P.A.s for all encounters

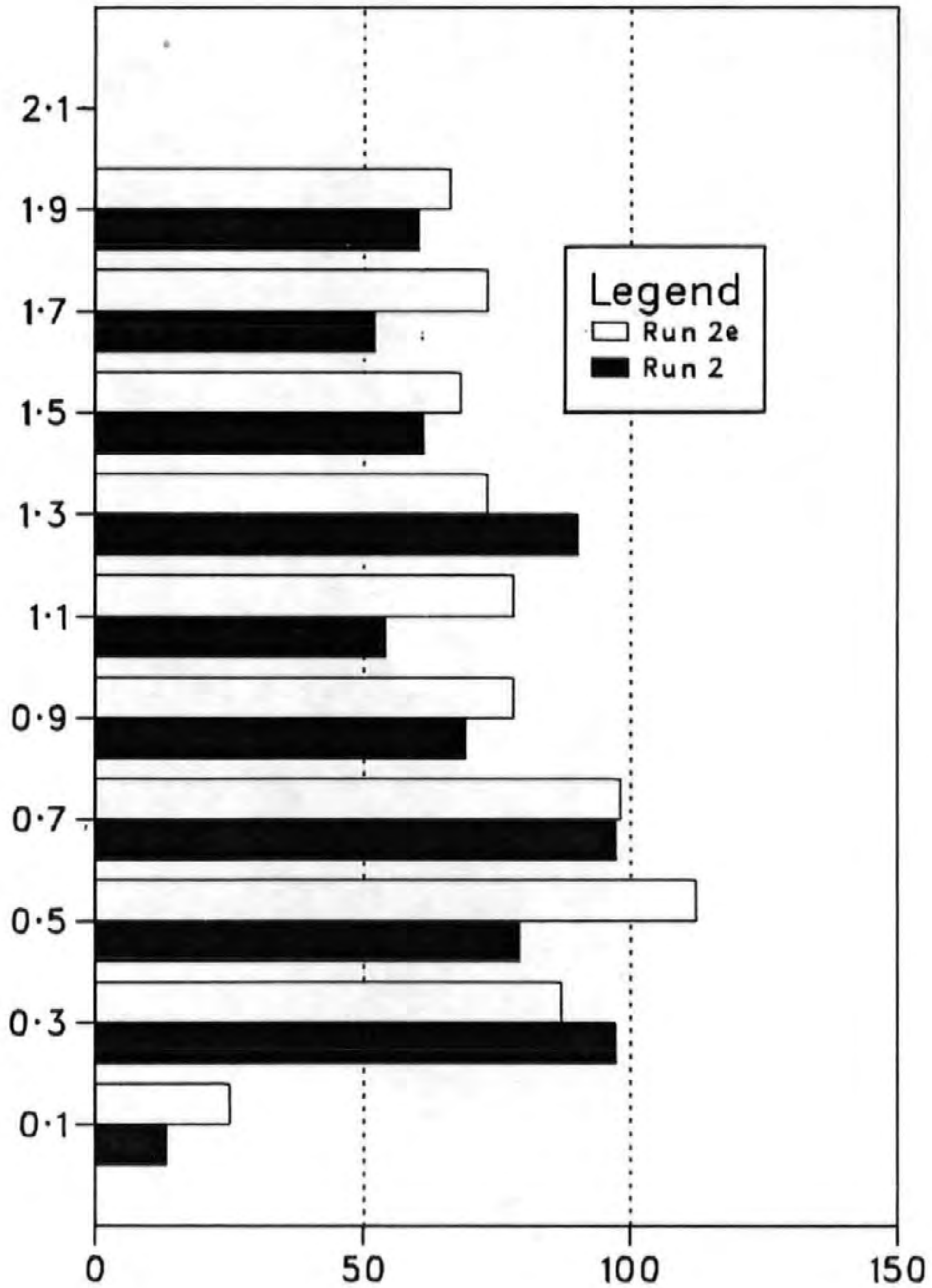


Fig.8.32 Distribution of C.P.A.s for head-on encounters

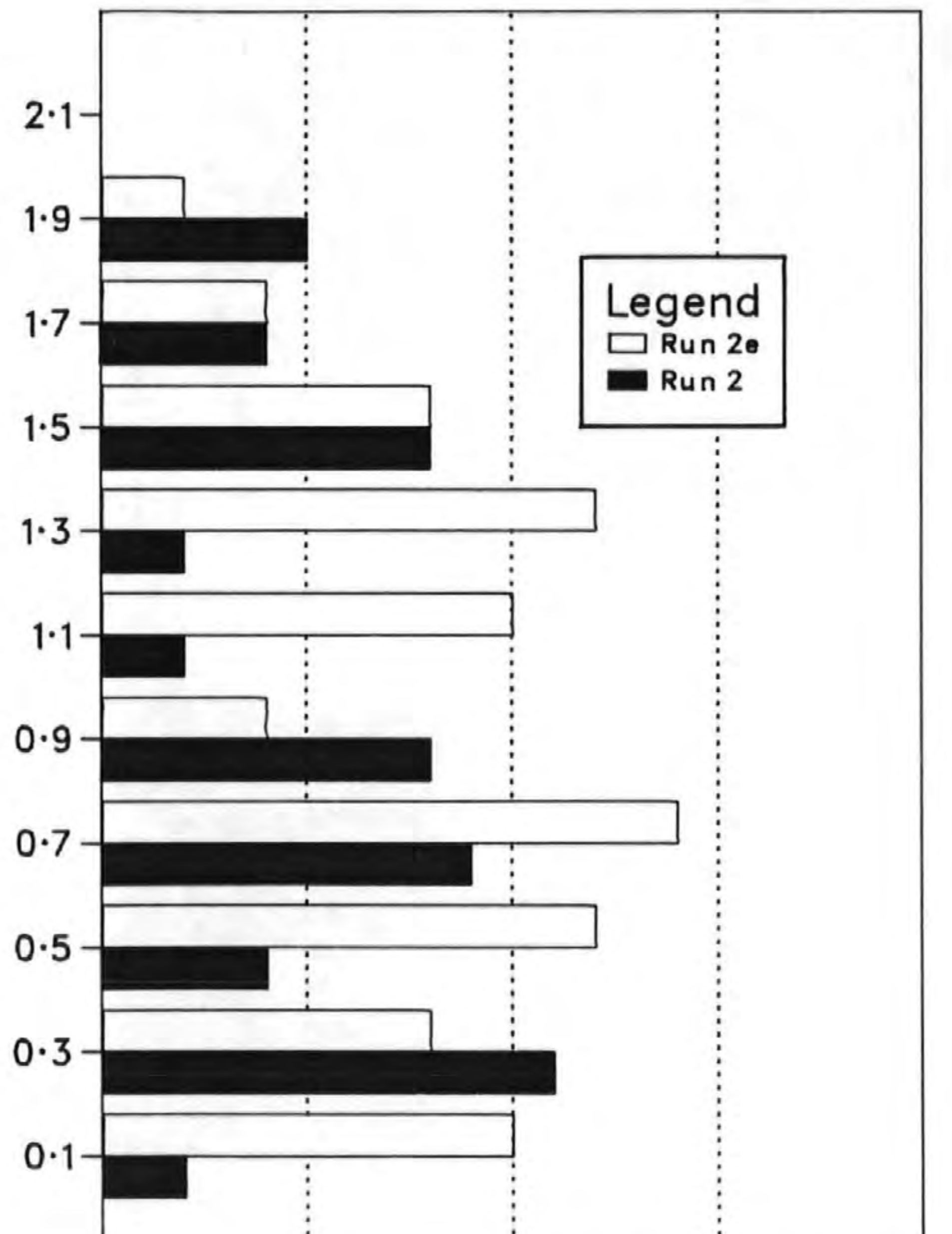


Fig.8.33 Distribution of C.P.A.s for crossing encounters

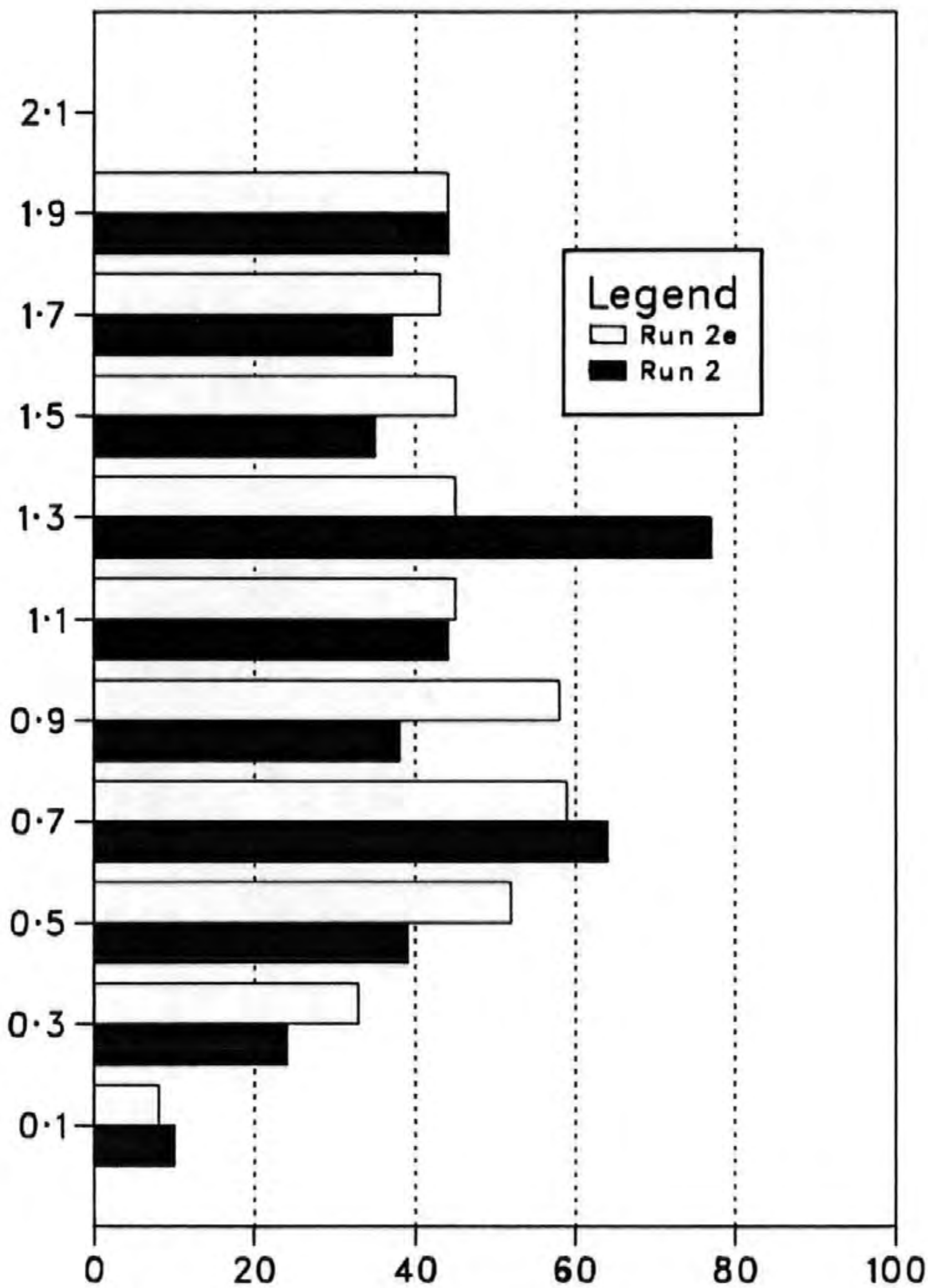


Fig.8.34 Distribution of C.P.A.s for overtaking encounters

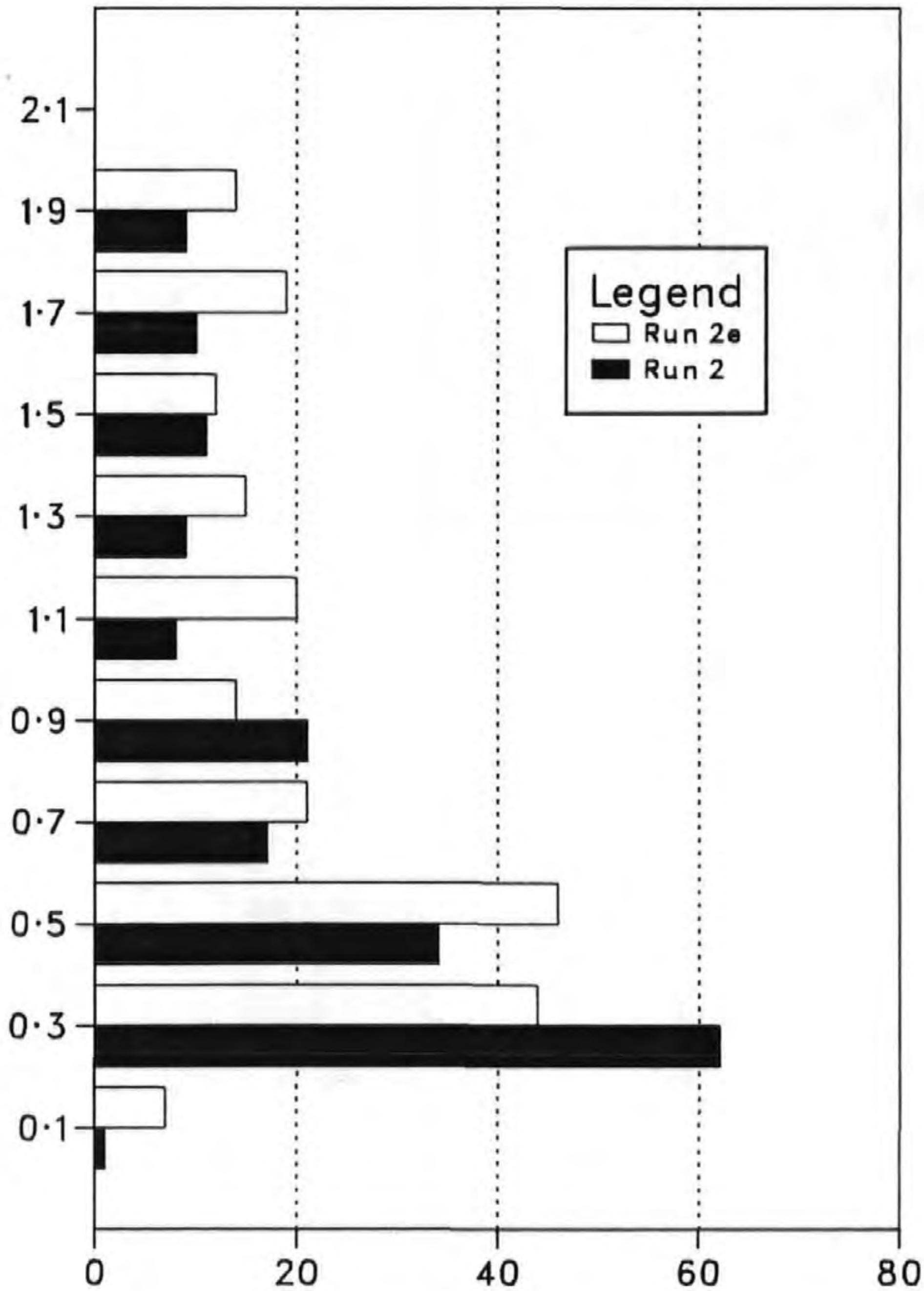


Fig.8.35a Run 2e - C.P.A.s <= 1.0

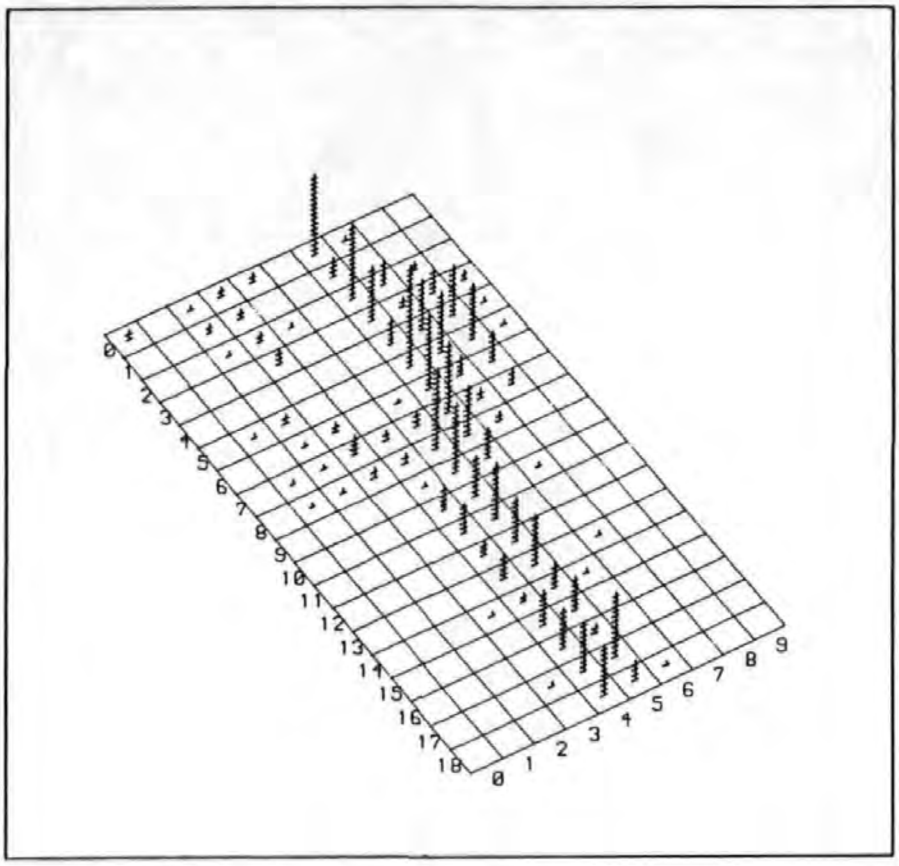
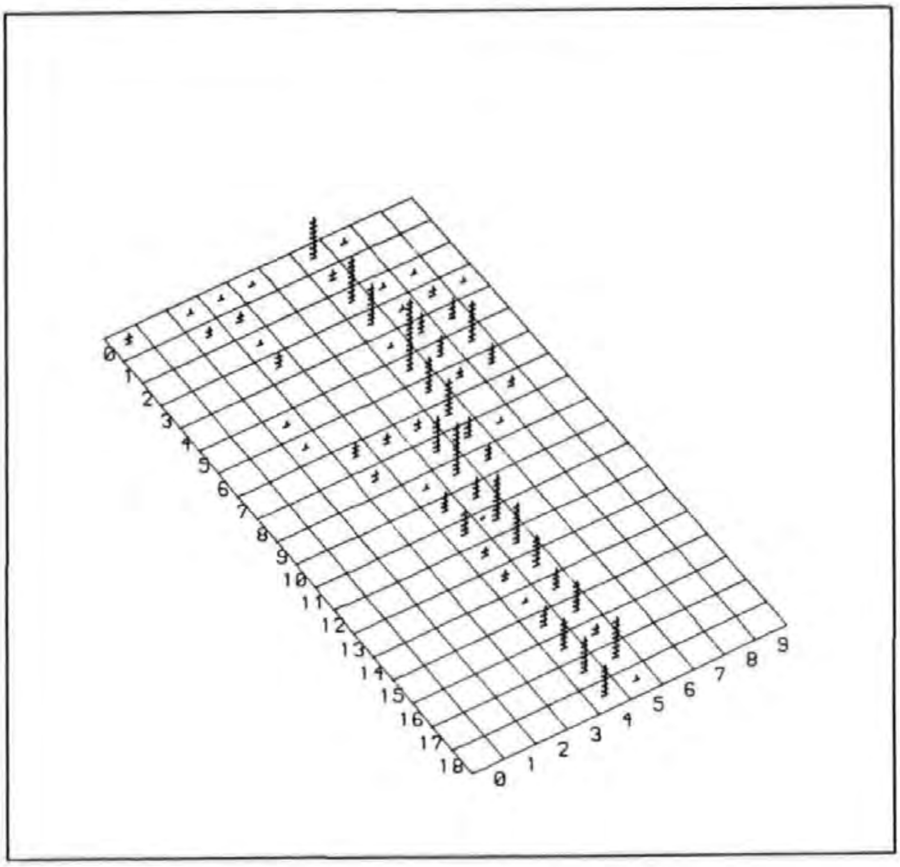


Fig.8.35b Run 2e - C.P.A.s <= 0.6



8.5 The effects of an increase or decrease in traffic volume

8.5.1 Introduction

The last complication to be considered by the computer simulation was the effect of an increase or a decrease on the volume of shipping. Run 2f ran the same amount of traffic in one day instead of two whilst Run 2g ran the same amount of traffic in four days. The result of this was that Run 2f was effectively double the normal density whilst Run 2g was half the normal density.

8.5.2 Distribution of through traffic at the Varne

It can be seen that the lateral distribution of through traffic at the Varne for Run 2g (Fig. 8.36) approached the no manoeuvre distribution displayed in Run 2a (Fig. 8.1), whilst that of Run 2f tended to increase the spread of the distribution. Again concentrating on the distributions to the north of the Varne: Run 2f had a mean passing distance of 1.39 n.miles and a standard deviation of 0.54; Run 2g had a mean of 1.13 and a standard deviation of 0.29 and Run 2 had a mean of 1.19 and a standard deviation of 0.44.

8.5.3 The distribution of the number of encounters

Figure 8.37 shows how the numbers of encounters for each type of encounter changed with the density of shipping. It can be seen that the total number of encounters increased by a factor of 2.6 for a doubling of density. For half the density of traffic, Run 2g, the total number of encounters reduced by a factor of 2.25. Clearly more data would be required to determine with any confidence the relationship between the density and the number of encounters.

8.5.4 The spatial distribution of encounters

Figures 8.38a-d and 8.39a-d show the spatial distributions for Run 2f and Run 2g respectively.

8.5.5 The distributions of the number of C.P.A.s

Figures 8.40 to 8.43 show the distributions of C.P.A.s for Runs 2f and 2g. The total number of C.P.A.s less than 1 n.mile increased by a factor of 2.05 for Run 2f and reduced by a factor of 2.04 for Run 2g. It can be seen that this approximates to a directly proportional relationship between the number of C.P.A.s less than 1 n.mile and the density of shipping.

8.5.6 The spatial distribution of C.P.A.s

Figures 8.44a-b and 8.45a-b show the spatial distribution of the numbers of C.P.A.s. The natural bottle-neck at the Varne can be seen quite clearly for the high density traffic.

Fig.8.36 Distribution of through traffic at Varne

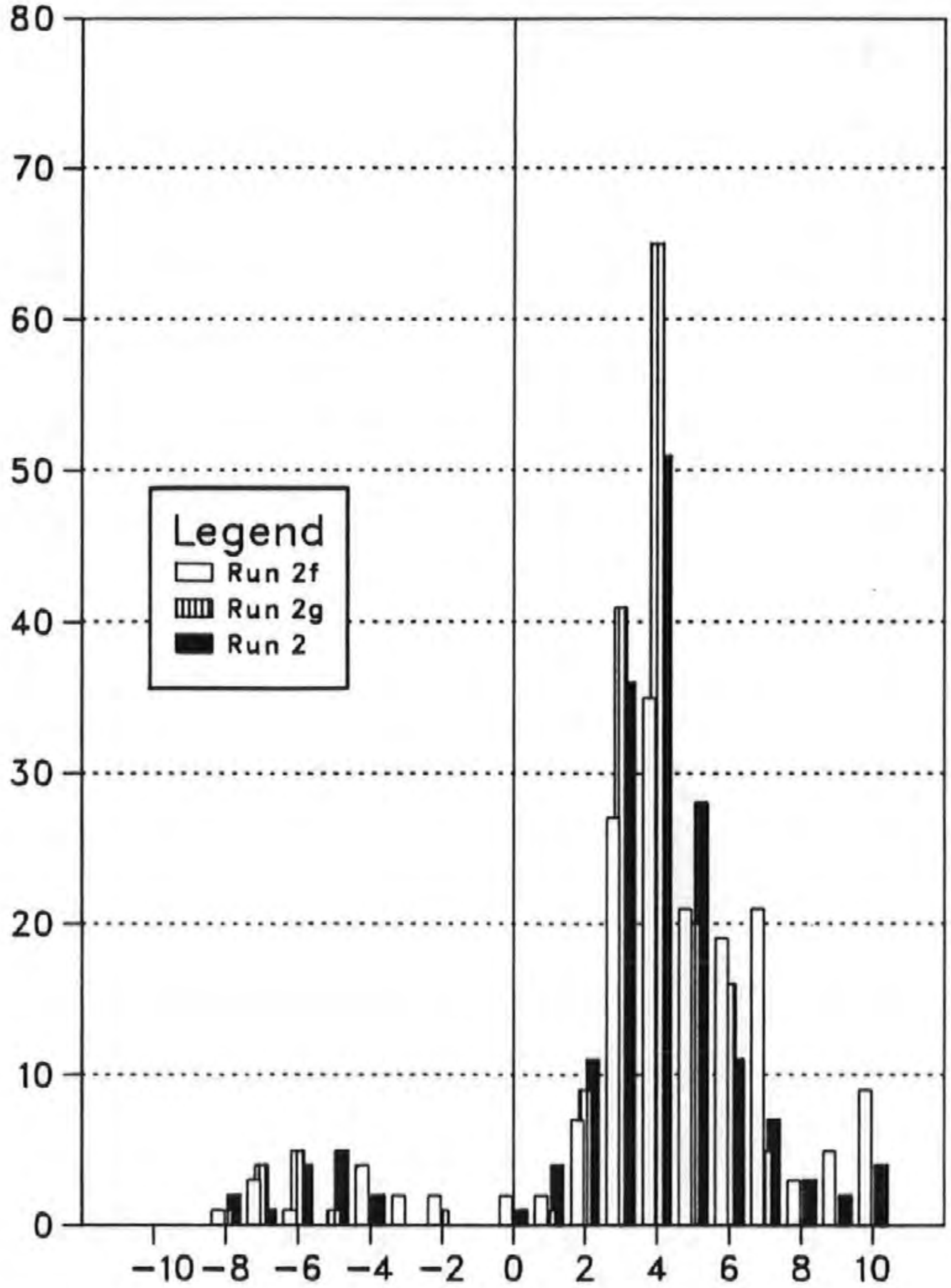


Fig.8.37 Distribution of encounters

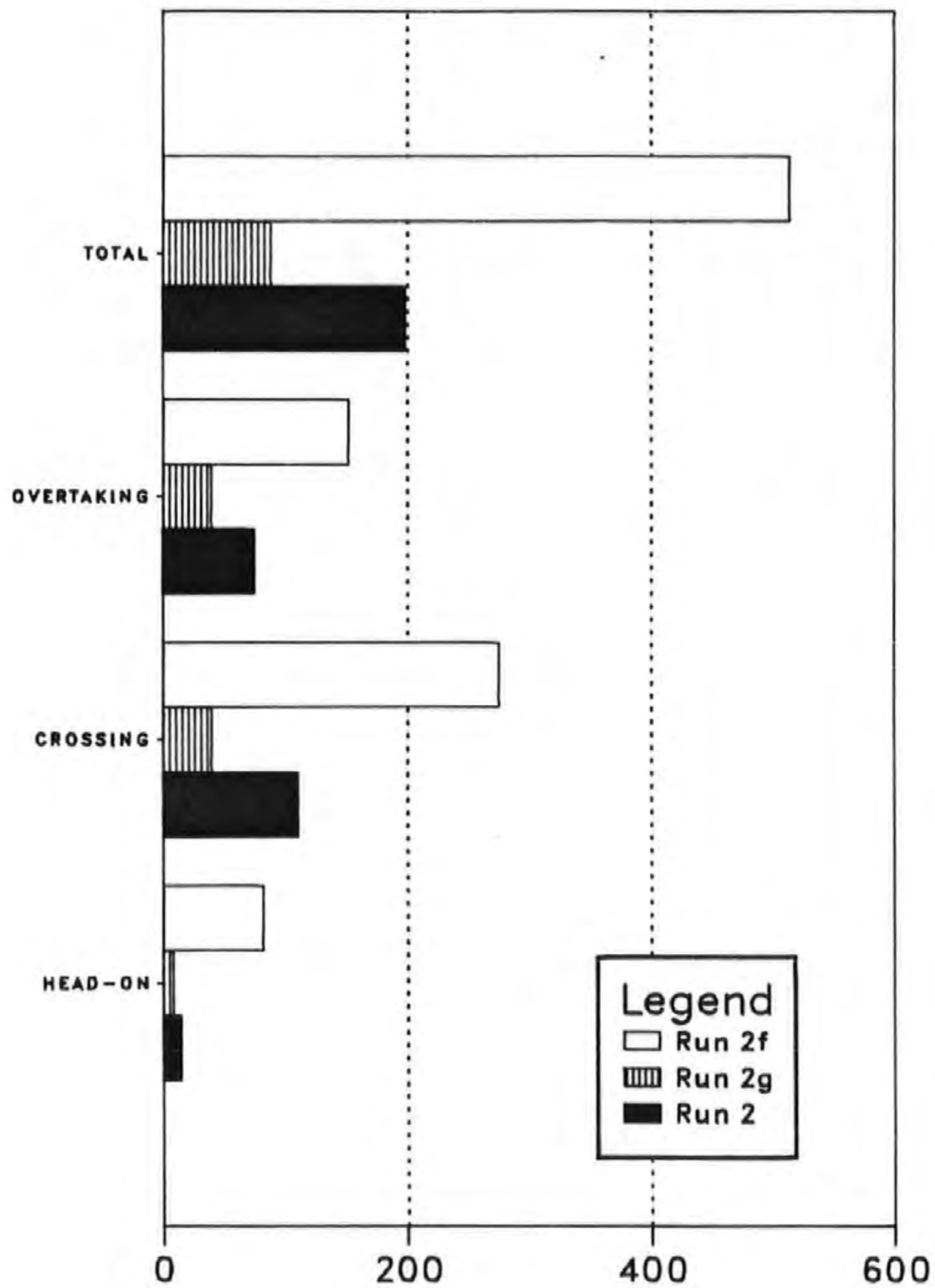


Fig.8.38a Run 2f – All encounters

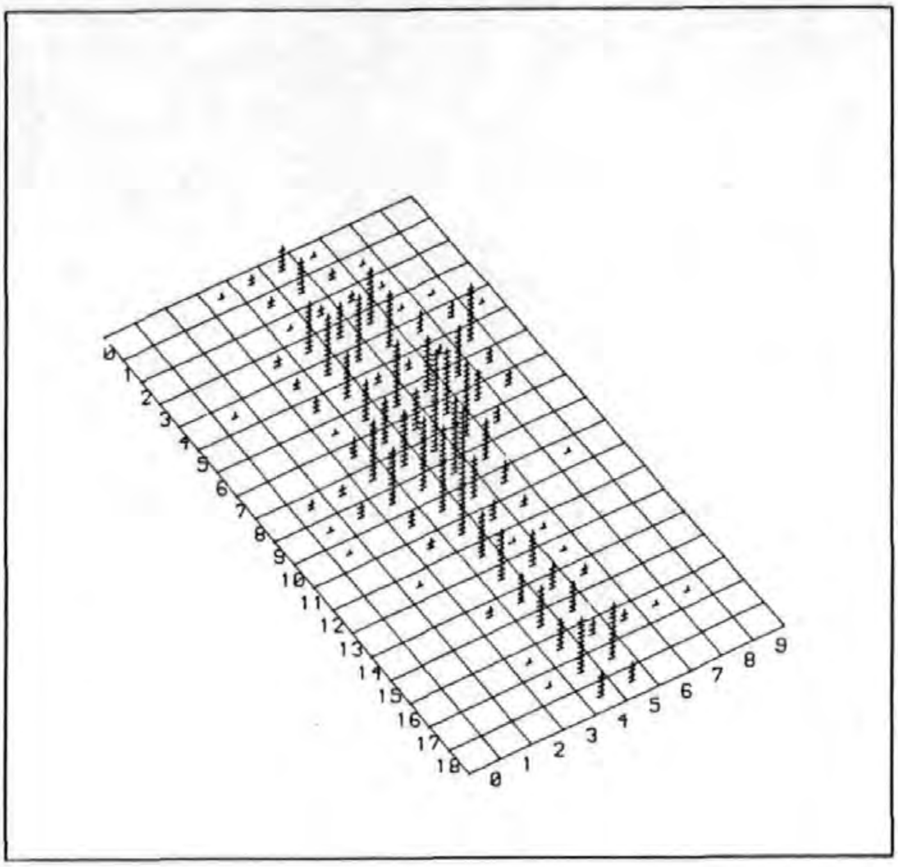


Fig.8.38b Run 2f – Head-on encounters

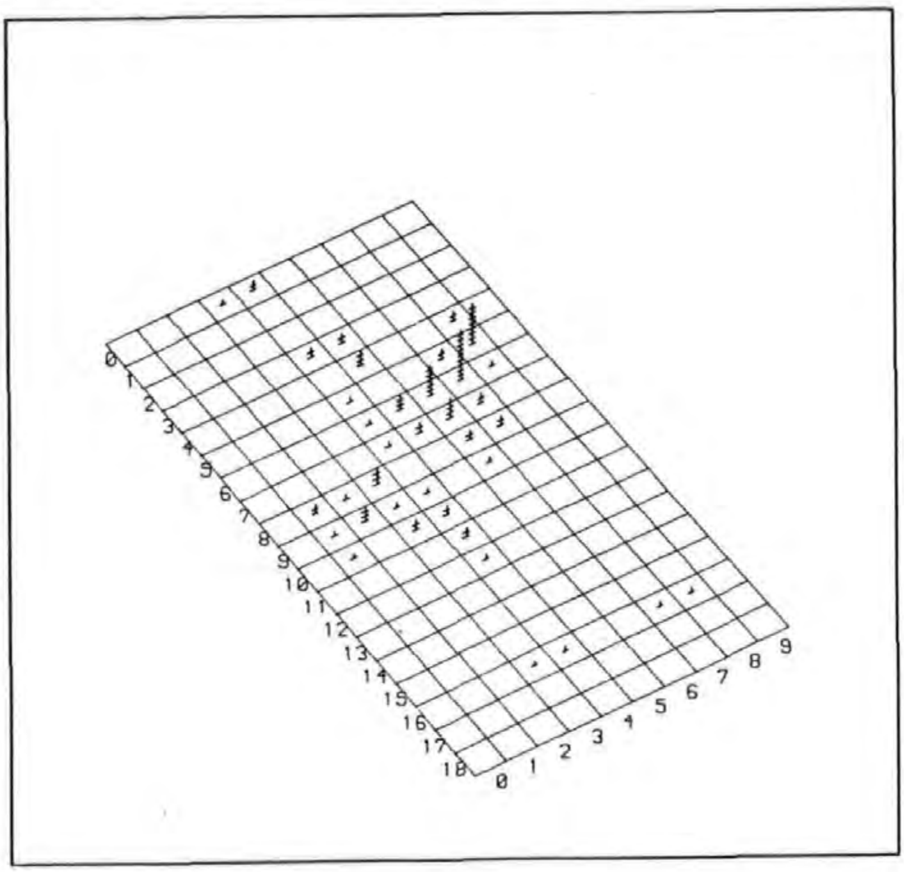


Fig.8.38c Run 2f – Crossing encounters

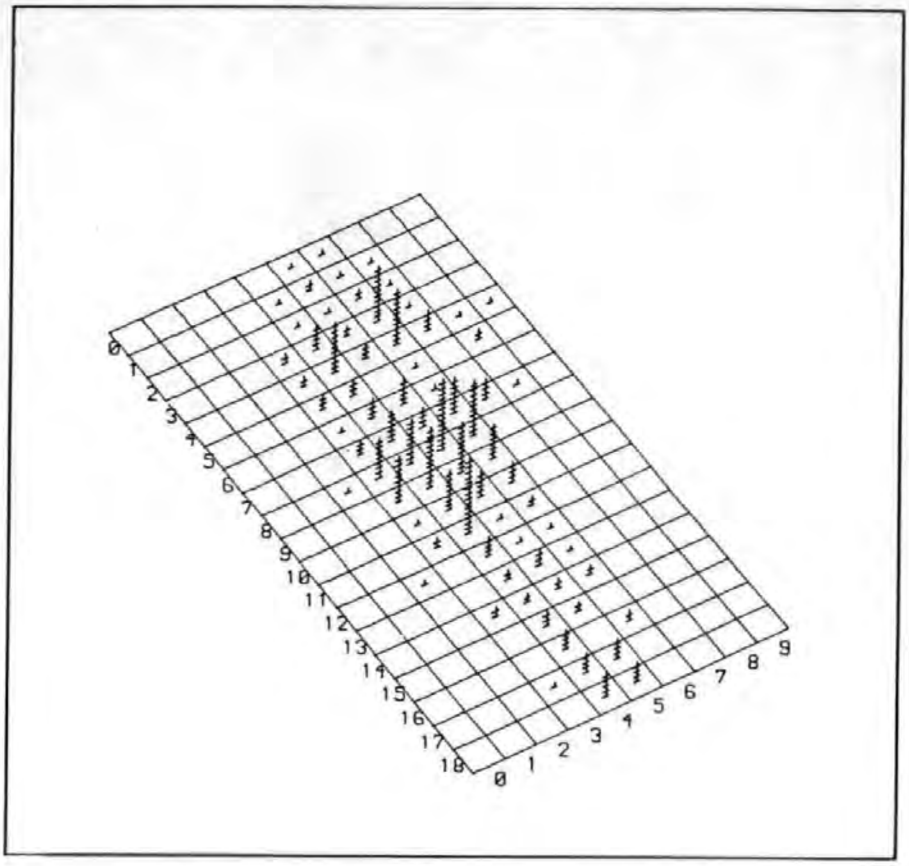


Fig.8.38d Run 2f – Overtaking encounters

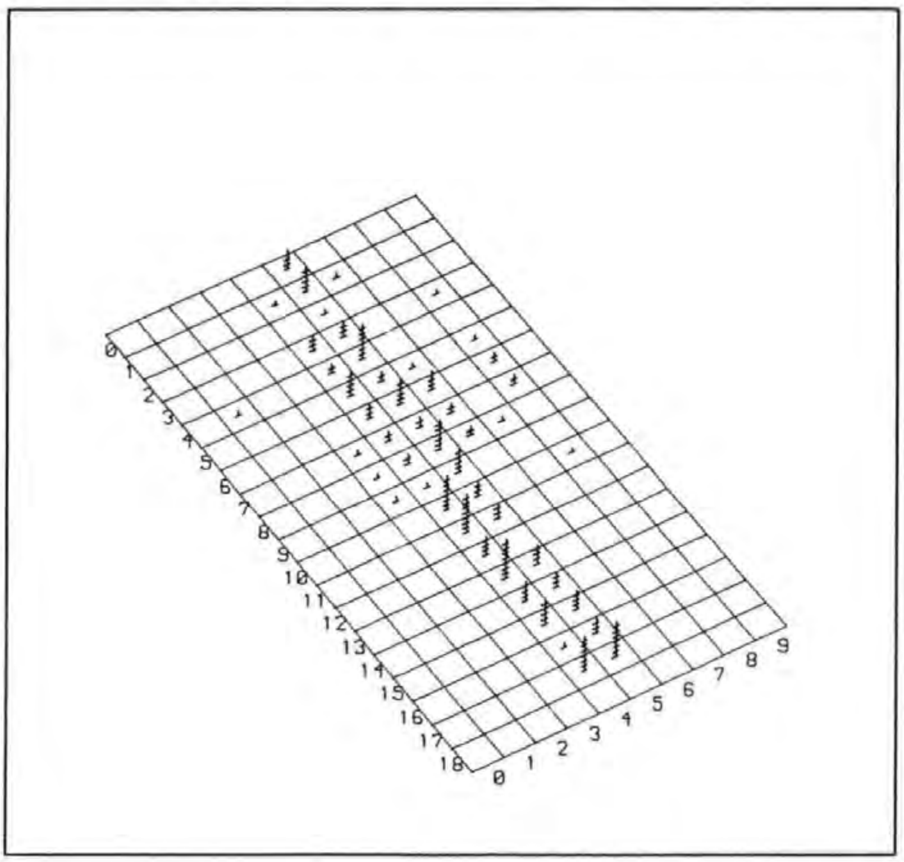


Fig.8.39a Run 2g – All encounters

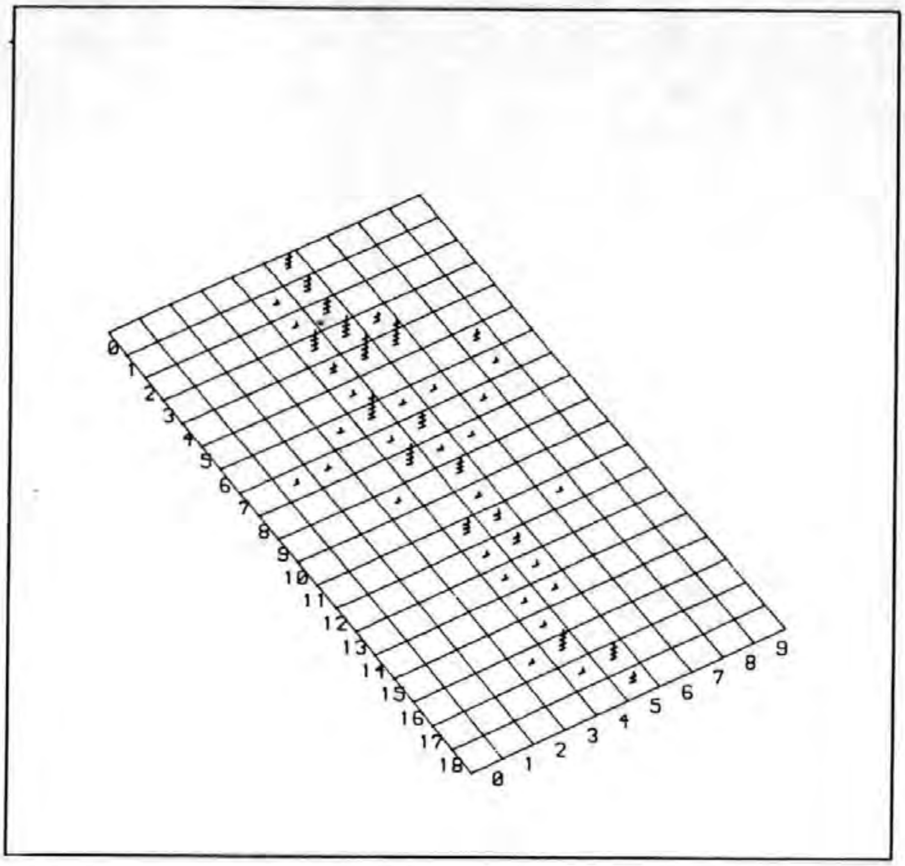


Fig.8.39b Run 2g – Head-on encounters

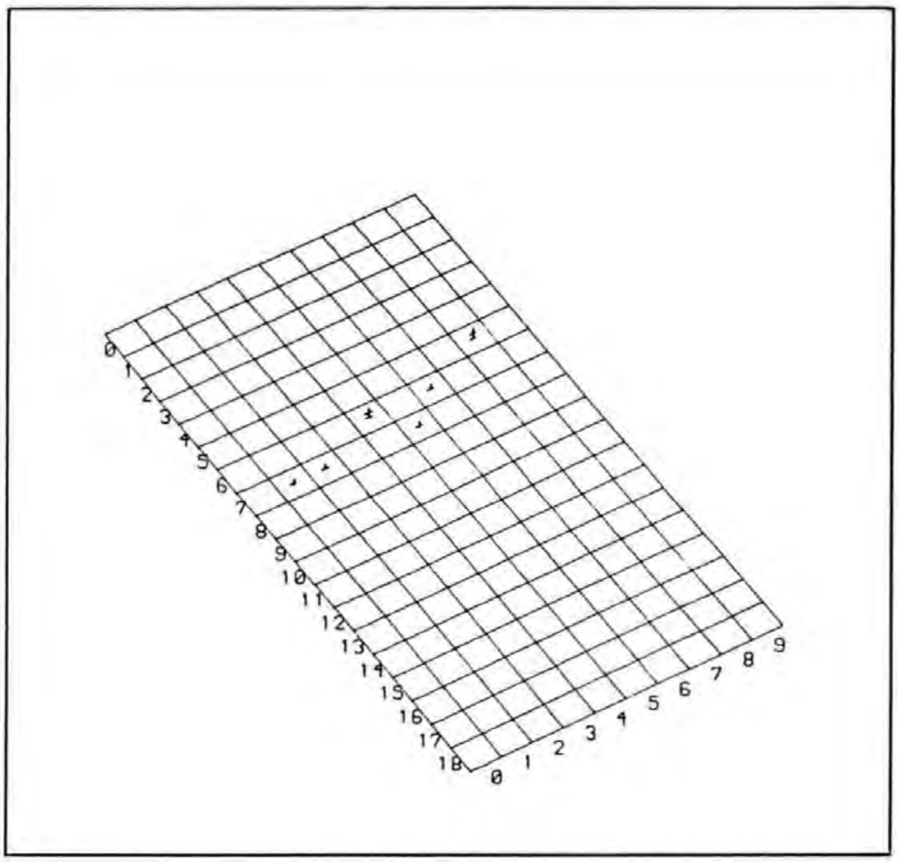


Fig.8.39c Run 2g – Crossing encounters

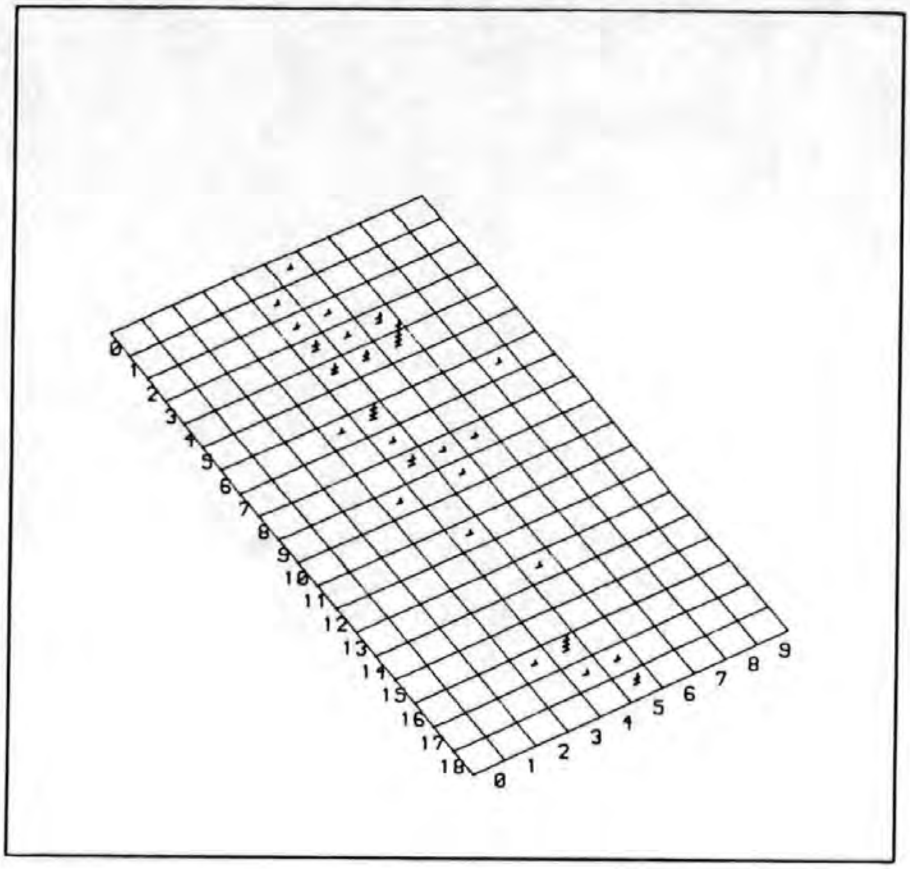


Fig.8.39d Run 2g – Overtaking encounters

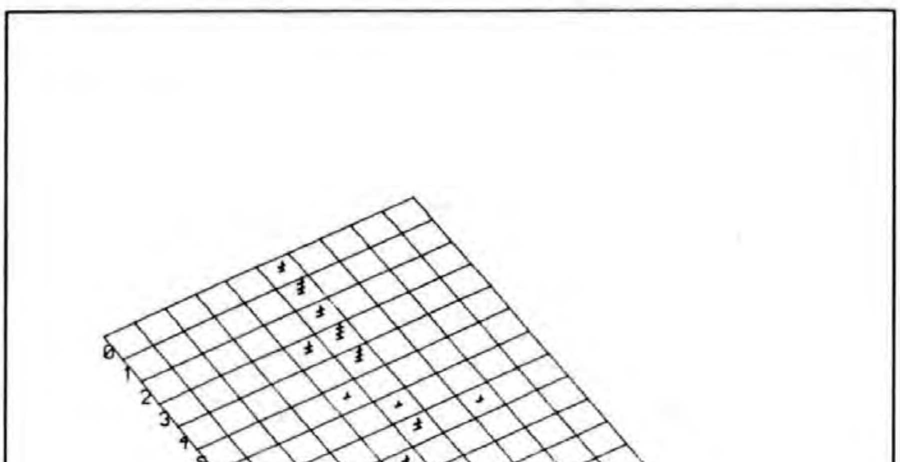


Fig.8.40 Distribution of C.P.A.s for all encounters

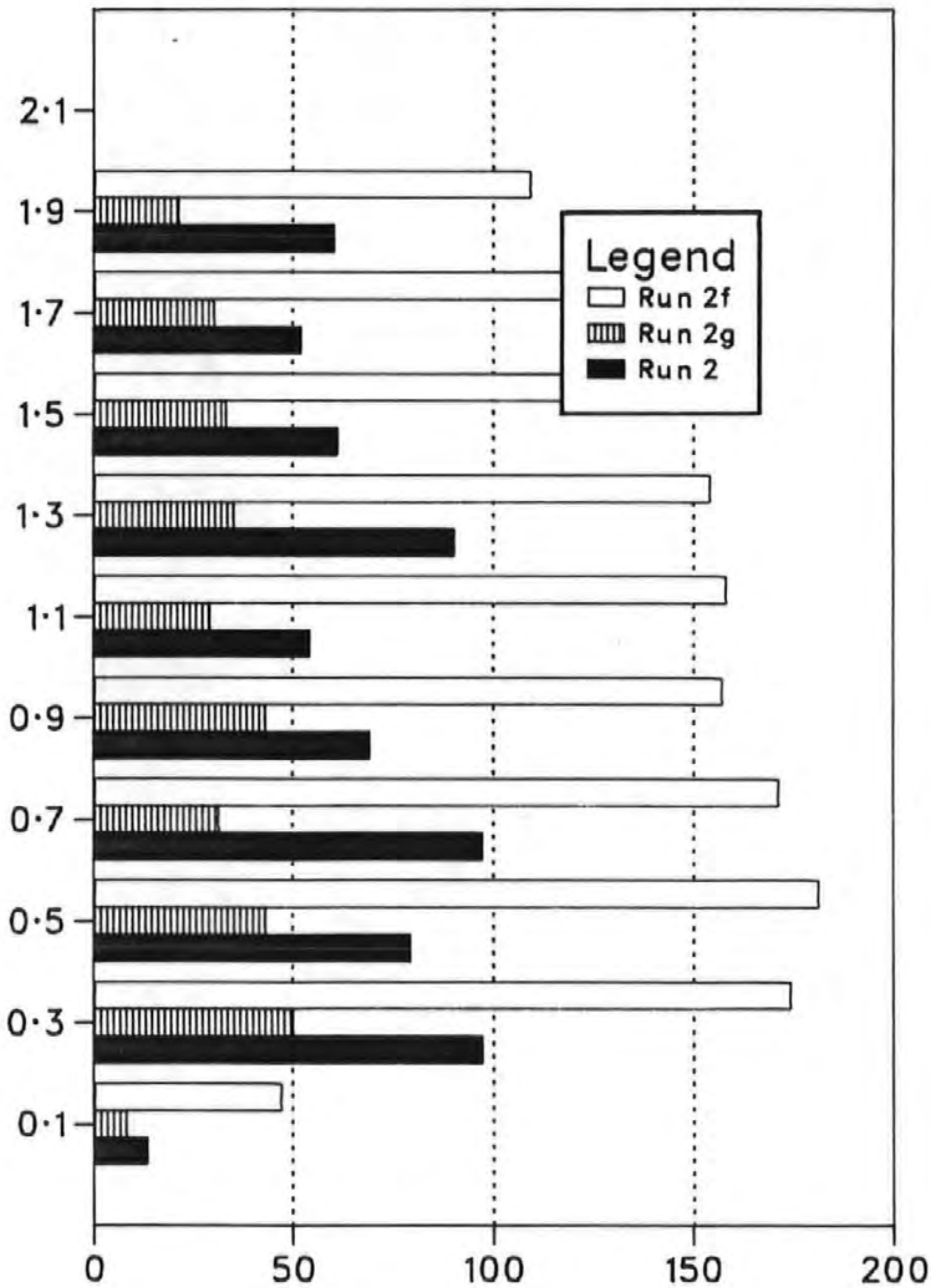


Fig.8.41 Distribution of C.P.A.s for head-on encounters

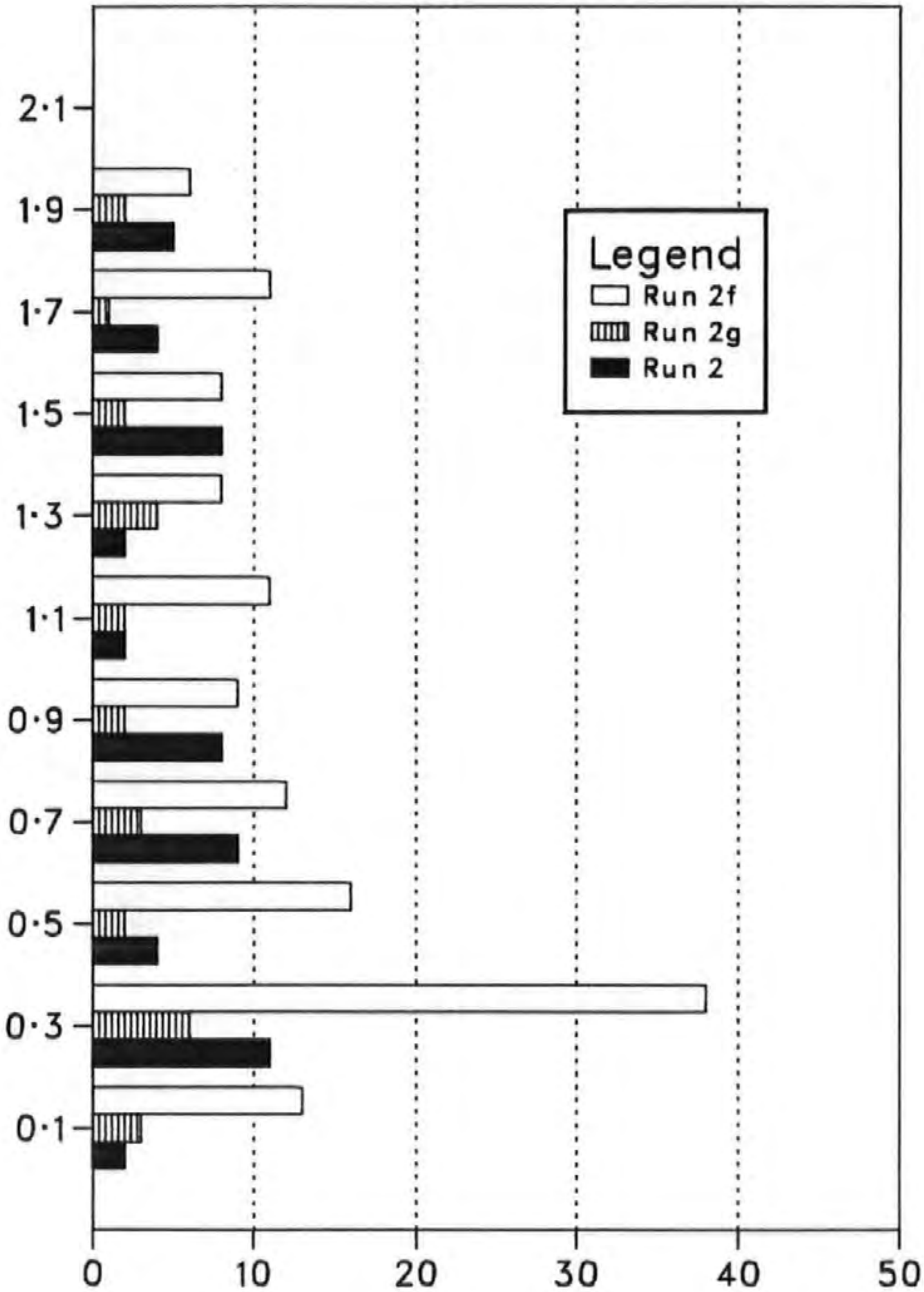


Fig.8.42 Distribution of C.P.A.s for crossing encounters

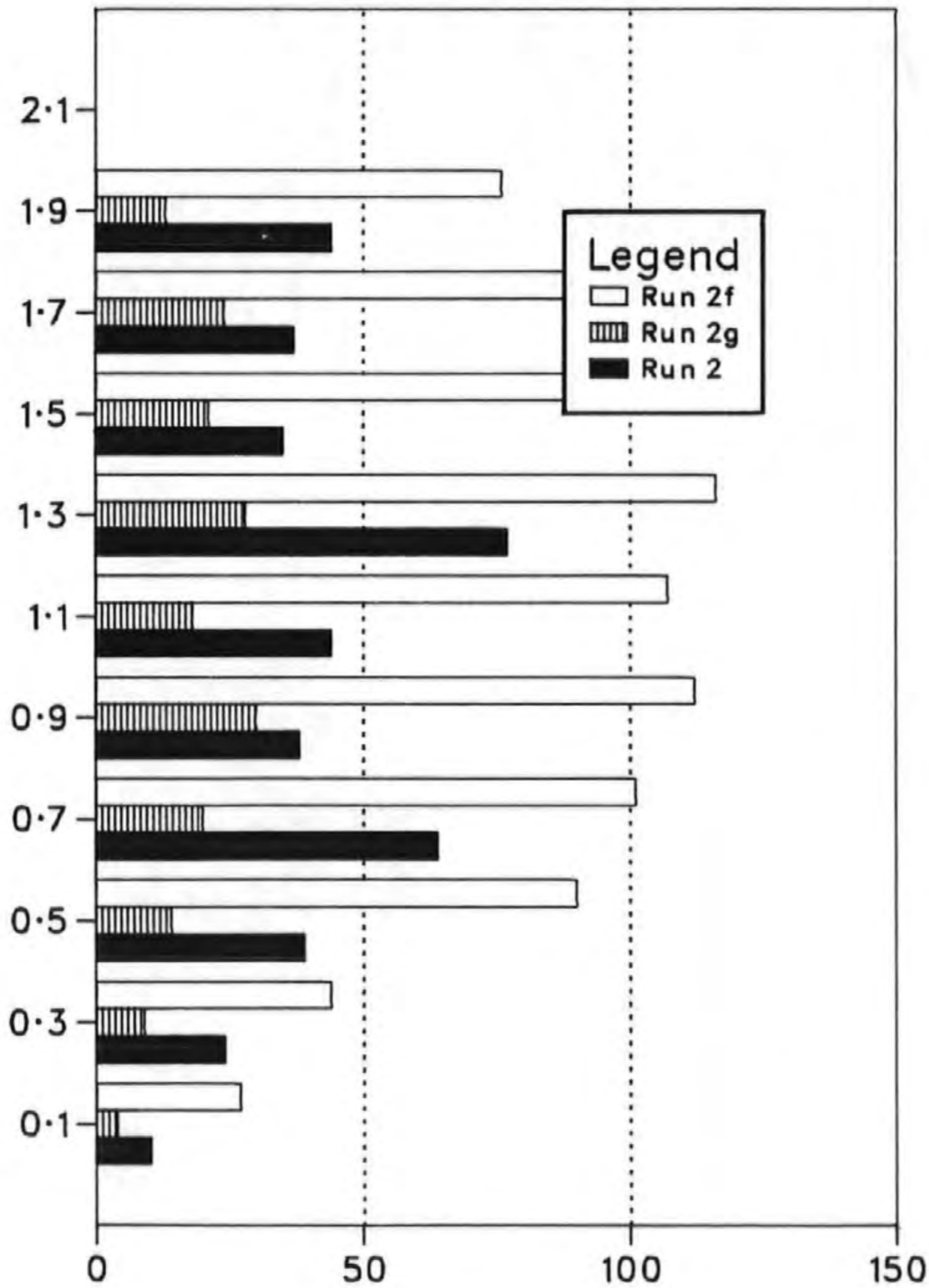


Fig.8.43 Distribution of C.P.A.s for overtaking encounters

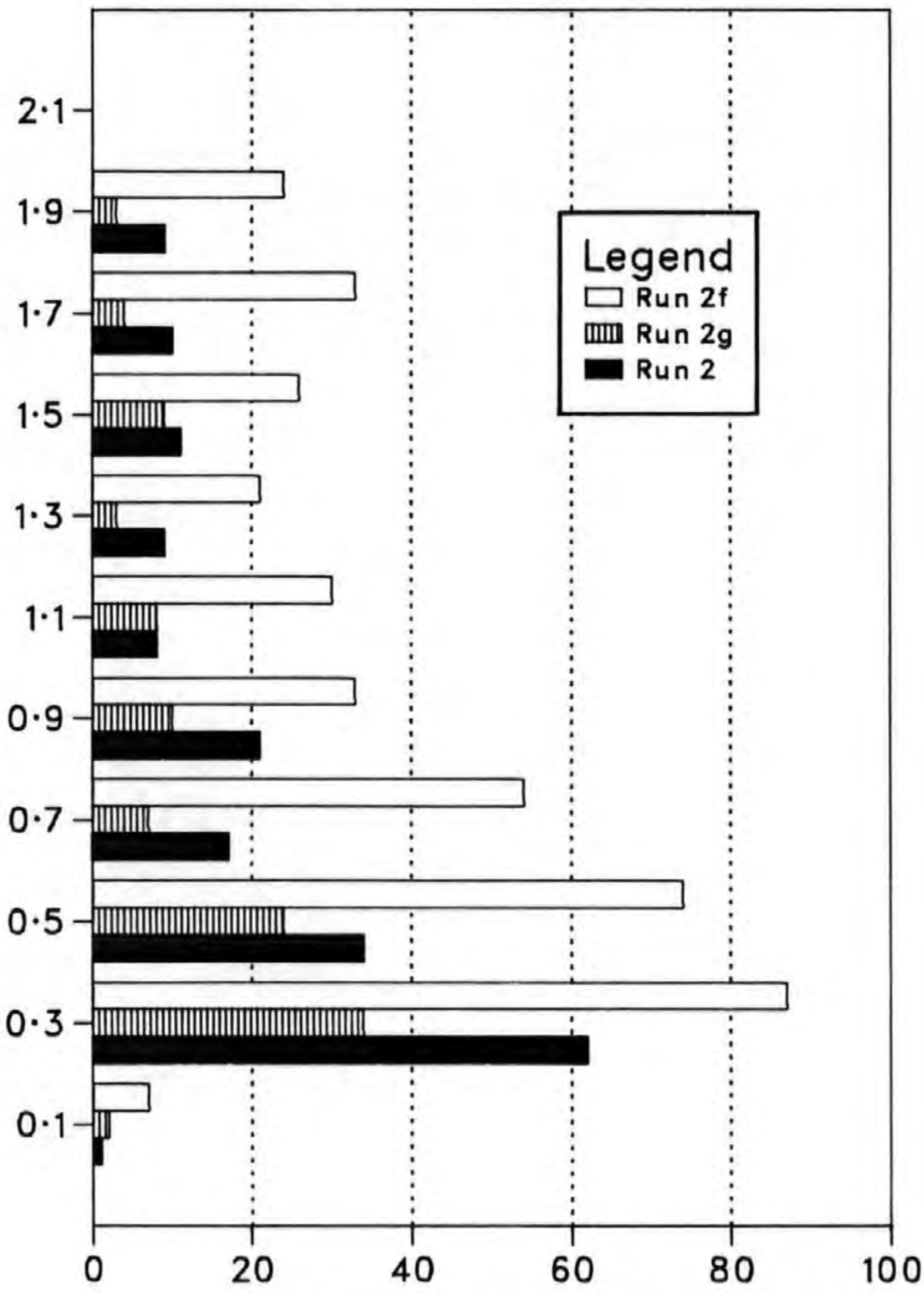


Fig.8.44a Run 2f - C.P.A.s <= 1.0

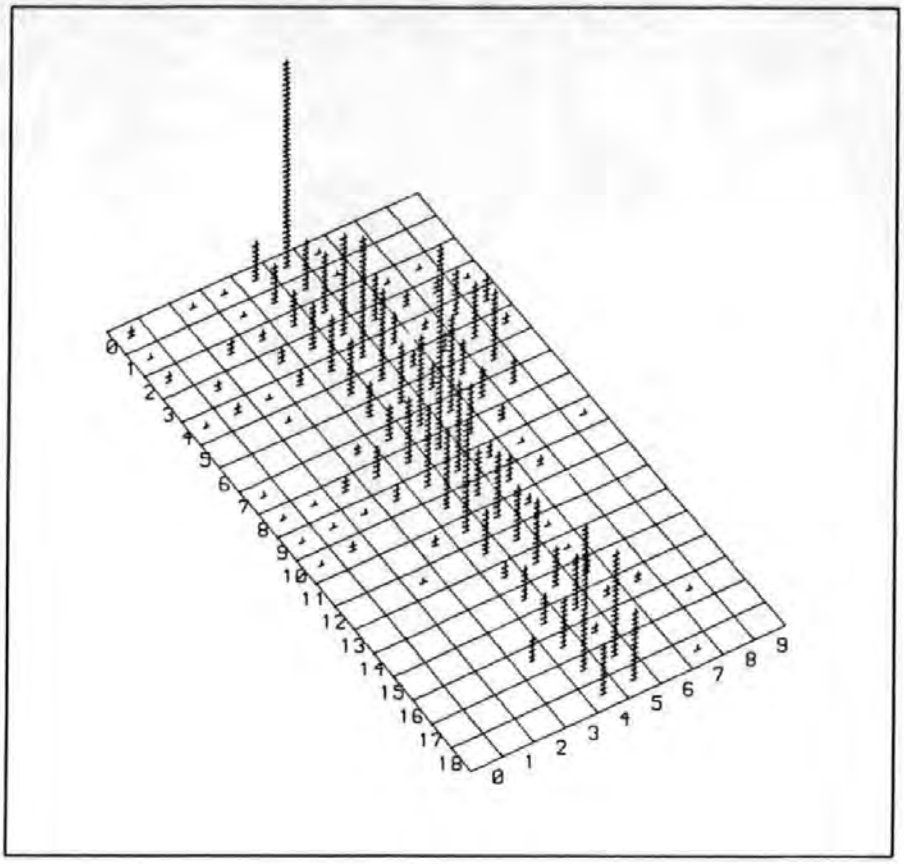


Fig.8.44b Run 2f - C.P.A.s <= 0.6

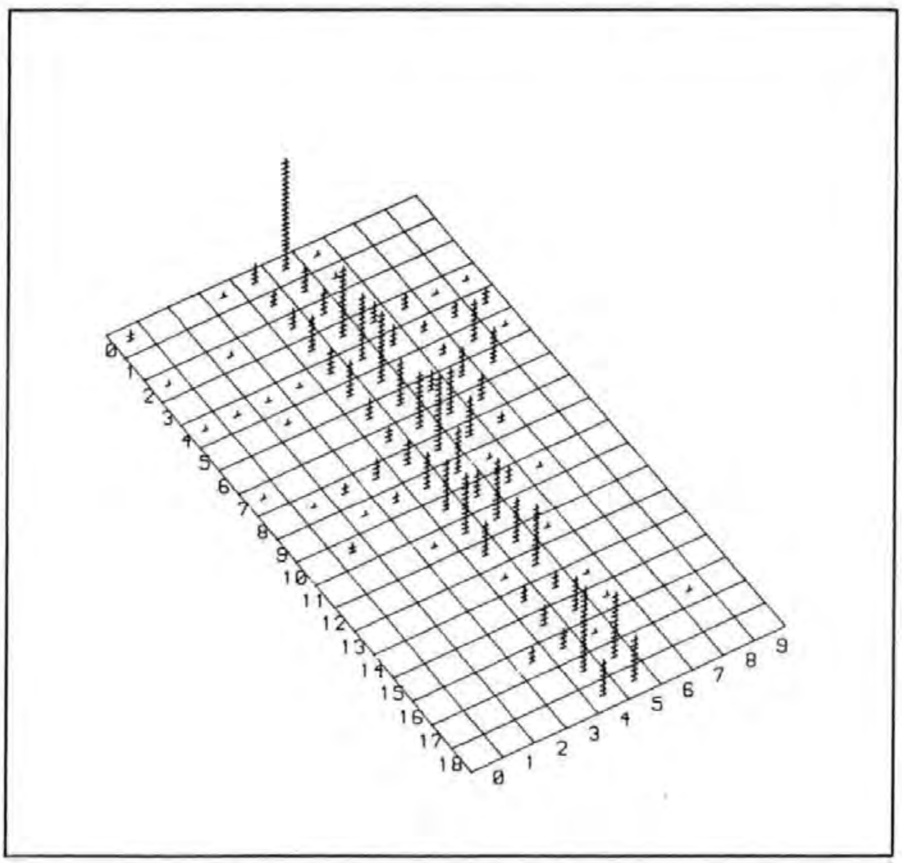


Fig.8.45a Run 2g – C.P.A.s <= 1.0

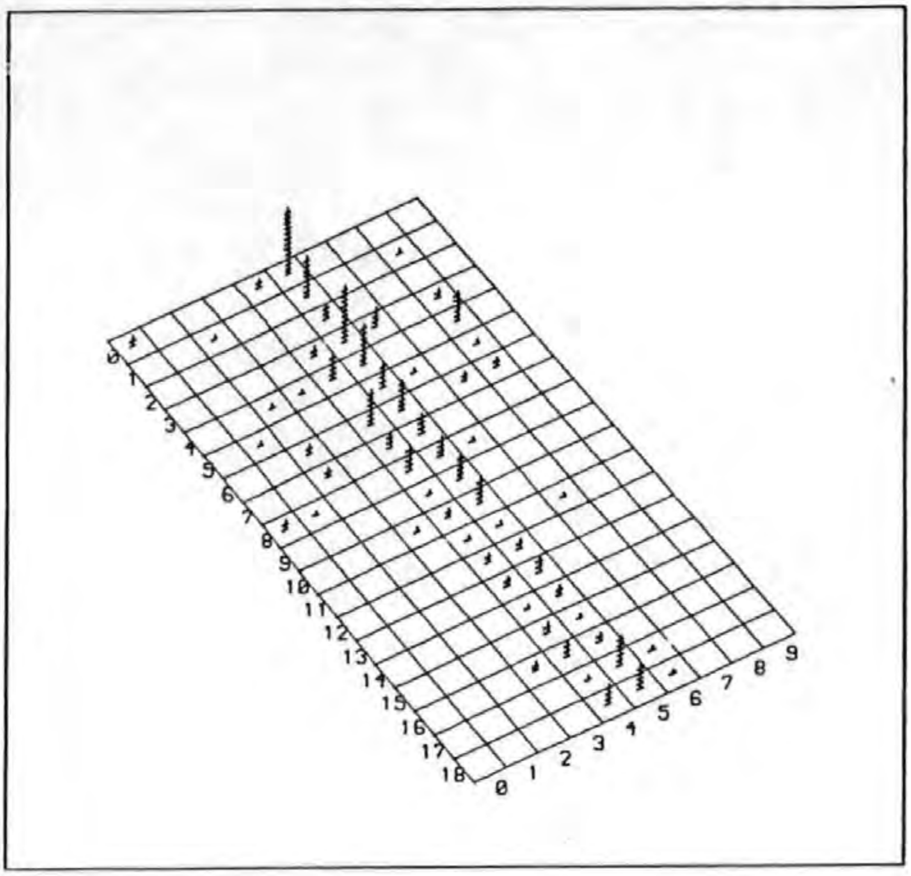
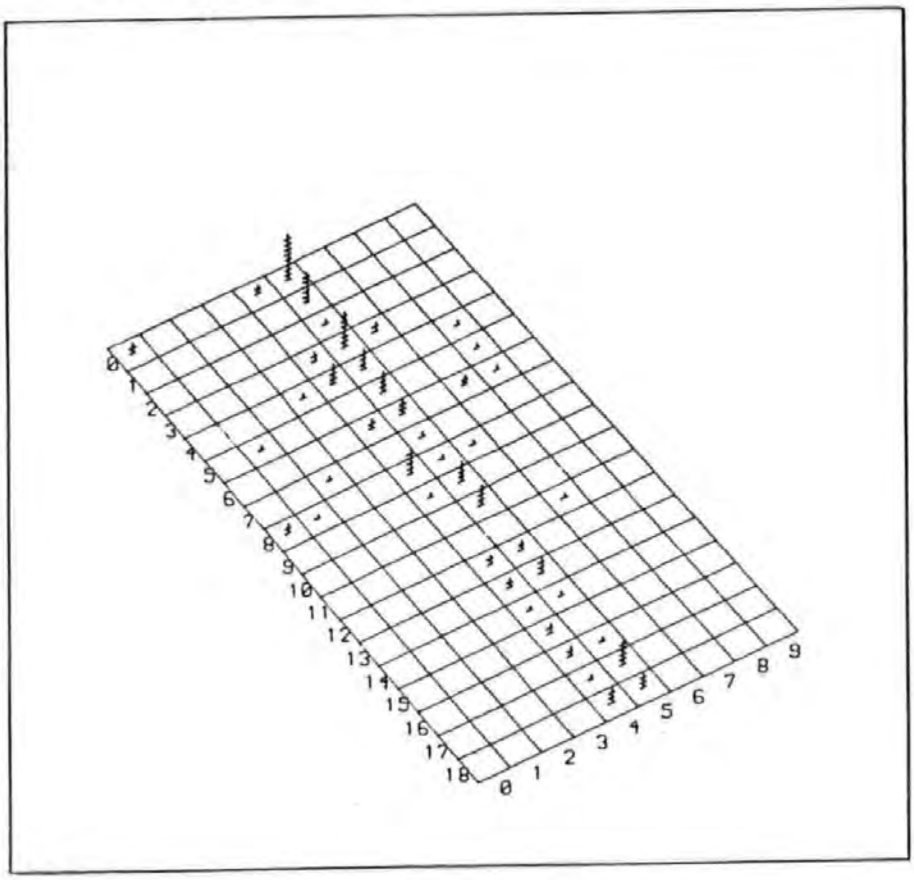


Fig.8.45b Run 2g – C.P.A.s <= 0.6



Chapter 9 The computer controlled radar simulation

9.1 Initial aims

The validation of the computer simulation of the Dover Strait was performed using two main approaches. These were best described as the qualitative and the quantitative approaches. The latter was used essentially to consider the results of the simulation of the area as a whole. The hypothesis being that if the inputs to the system were chosen correctly then the outputs from the system (flow rates, distributions, numbers of encounters etc.) would bear a statistical similarity to the real system. The former was judged to be the most practical means of validating the simple model (the simulation of the encounter alone), and consisted of showing graphical records of ships′ tracks for different encounter situations to experienced mariners′. Although, in general, mariners′ responses to the ships′ manoeuvres were favourable, it was decided that this form of validation was unrealistic, depending to a great extent on the subject having the ability to relate the track plot to a similar situation experienced at sea. It was concluded that some other method of demonstrating the model′s behaviour was required, in which the mariner could observe the situation developing in a more meaningful, and consequently useful manner.

The subsequent development was the display, in real time, of the simple encounter model exercises on a SIGMA colour graphics terminal. The ships were represented by green squares on a black background. As in the previous simulation ships updated their positions every 20 seconds, but the squares were not erased from the screen for six iterations or two minutes. The reason for this delay was to allow observers a means of deducing the speed of the vessels involved in the example, hence the longer the visible track the faster the vessel. This progressed then to a colour graphics representation of an exercise from the simulation of the Dover Strait, in which the land, buoys and routing scheme boundaries were displayed. Several of the simple ship encounter "runs" and a longer "run" of vessels through the Strait were recorded on video tape, and used to demonstrate the model, in an invited lecture presented to the Royal Institute of Navigation (Colley et al., 1983). This achieved one of the aims of the graphics representation, allowing the characteristics of the simulation to be judged by several of the leading experts in the marine field. The computer simulated runs appeared to be favourably received by those present.

It was felt that there existed still an artificiality to the qualitative validation, in that the role of the mariner was that of an "unconcerned" spectator. It was decided that the ideal means of observing a mariner's responses to the model was to allow him to take an active part in the exercise, since this was clearly the way in which a mariner normally observed encounters, allowing the comparison of encounters between other vessels and between other vessels and his own ship. Not only then was the interest of the mariner retained by giving him some responsibility, but a further invaluable source of data on mariners' reactions was conceived.

An attempt was made to use the computer model to control the targets in an exercise on the Polytechnic simulator (Section 2.2.2). This proved to be impossible because there was not enough free programming space in which to reproduce the necessary coding, nor was the interfacing of an independent computer feasible due to the complexity of the simulator's construction. The decision was made subsequently to modify the successful graphics display computer model to simulate the Plan Position Indicator (P.P.I.).

9.2 The development of the mariner controlled model

The development of the mariner controlled model from the simple ship encounter model was considered in five main sections:

a) the introduction of delays into the system, so as to run in real time;

b) the presentation of the P.P.I. so as to achieve the necessary degree of reality without being too costly in terms of computer time;

c) the possible display options available to the mariner on request;

d) the means of altering course and/or speed by the mariner when ordered;

e) the means by which information regarding the aspect of the target could be portrayed, so as to enable the exercise to be regarded as having been run in good visibility.

9.2.1 Operation in "real time"

The iteration time of 20 seconds used in the previous simulations was considered to be the optimum value that could be used in this case. The choice of a smaller time iteration would, in cases of high load on the system and/or encounter situations in the simulation, have resulted in the execution taking longer than the time period that it was supposed to represent. The use of a longer iteration period would have created an artificial atmosphere to the simulation with vessels remaining stationary for long periods of time and any alterations of course being over staggered. The running of the program in real time was achieved by determining the actual time taken by the computer to execute the iteration and then applying a delay to increase the total time taken to 20 seconds.

9.2.2 Presentation of the P.P.I.

The following standards of presentation for the P.P.I. were decided upon:

a) the P.P.I. boundary was to be represented by a thin green cirle and was to be as big as could reasonably fit into the available screen area;

b) the targets were to be represented by green filled circles 2mm in diameter. Although it was recognized that the size of the radar echo changed with the size of the target, the aspect, the distance from the receiver etc., it was decided that the use of a constant size was justifed;

c) a dashed line from the mariner driven vessel to the edge of the radar screen was used to represent the heading marker;

d) a permanently displayed time (hours and minutes), bearing and speed;

e) a large letter "N" to represent North.

It had been hoped initially to include also the bearing markers in 10 degree increments around the face of the P.P.I., but it was found to be impractical due to the time needed for the computer to reproduce the image on updating. It had further been the aim to enable the mariner to determine the distance of vessels from his ship by including some form of variable range marker. This facility proved to be unsatisfactory, requiring a great deal of line drawing and deleting, with the added complication that the moving line had the effect of deleting the ships' echoes.

9.2.3 Options available on request

The most difficult task encountered in the construction of the radar simulator program was the means of permitting the mariner, via the operator, to halt the "run" and make changes to the parameters. A means was eventually found by executing a controlled break into the program. It should be noted that this program required several non-standard Fortran commands and as a consequence is not automatically compatible with other computer systems running Fortran. Thus on activating the break key, a "menu" of options was displayed (Fig.9.1). The following options allowed the mariner to alter the presentation of the simulated P.P.I.:

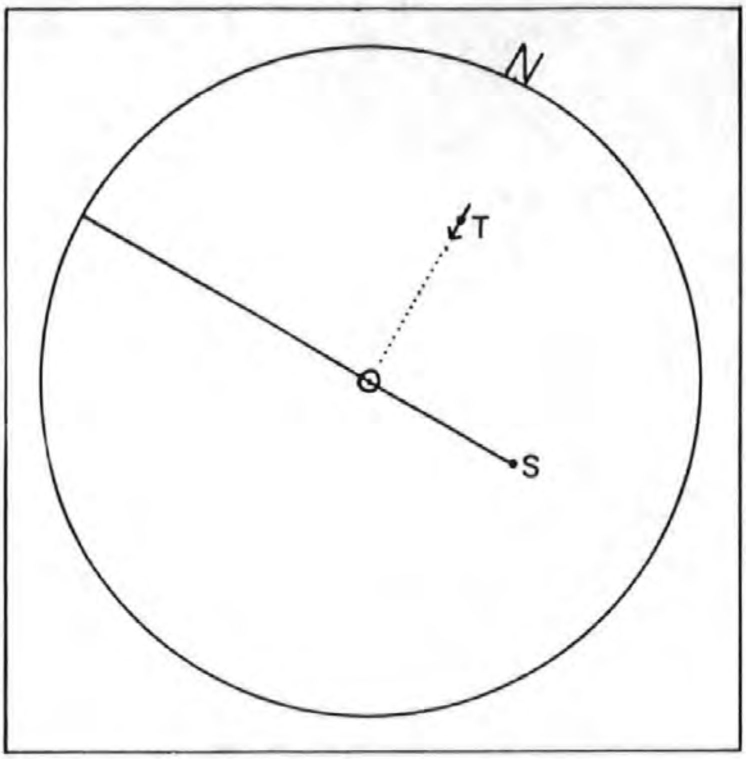
COURSE	- 1	New course, % of rudder
SPEED	- 2	Full - 4, Full (man.) - 3 Slow - 2, Dead slow - 1 Stop - 0
RADAR TYPE	- 3	True - 1, Rel. (North-up) - 2 Rel. (Ship's head-up) - 3
SHIPS ASPECT	- 4	
ABORT JOB	- 5	
DISPLAY MENU	- 6	
CONTINUE RUN	- 7	
RADAR RANGE	- 9	
GRID POSITION	- 10	Position is (x , y)
ENCOUNTER STATE	- 11	Distance apart is d n.miles Relative bearing is 0 degrees

Figure 9.1 Menu displayed on terminal at request, with the subsequent requests or information also shown

a) Radar range The mariner could choose any radar range from 1.5 miles up to 24 miles;

b) Radar mode The option was given to alter the mode of the radar presentation. On start up it was automatically in True Motion (T.M.) but at any time the display could be switched to Relative Motion Ship's-head Up (R.M.S.U.) or Relative Motion, North Up (R.M.N.U.). In T.M. mode the display was stabilized with the own-ship starting at a point mid-way between the centre and the circumference of the circle, in the opposite direction to the ship's initial heading (Fig.9.2). This was so that a greater area was displayed ahead and abeam of the own-ship and therefore allowing more time to detect the more rapidly developing head-on and crossing encounters. No automatic facility was provided to update the T.M. mode when a vessel was coming towards the edge of the circle, but the same effect was achieved by the operator resetting the mode. Both relative motion modes were obtained by placing the own-ship at the centre of the simulated P.P.I., and then calculating the vector addition of its velocity with each of the targets to obtain their graphical position. An alteration of course was observed as a rotation and shift of the heading marker in the T.M.N.U. mode (Fig.9.3), a rotation only in the R.M.N.U. mode and a rotation of the "N" marker in the R.M.S.U. mode (Fig.9.4).

It was the effective rotation of the rim of the radar screen as the mariner driven vessel altered course, in the R.M.S.U. mode, that prevented the inclusion of the bearing in degrees around the rim, as clearly when the markings rotated it involved redrawing



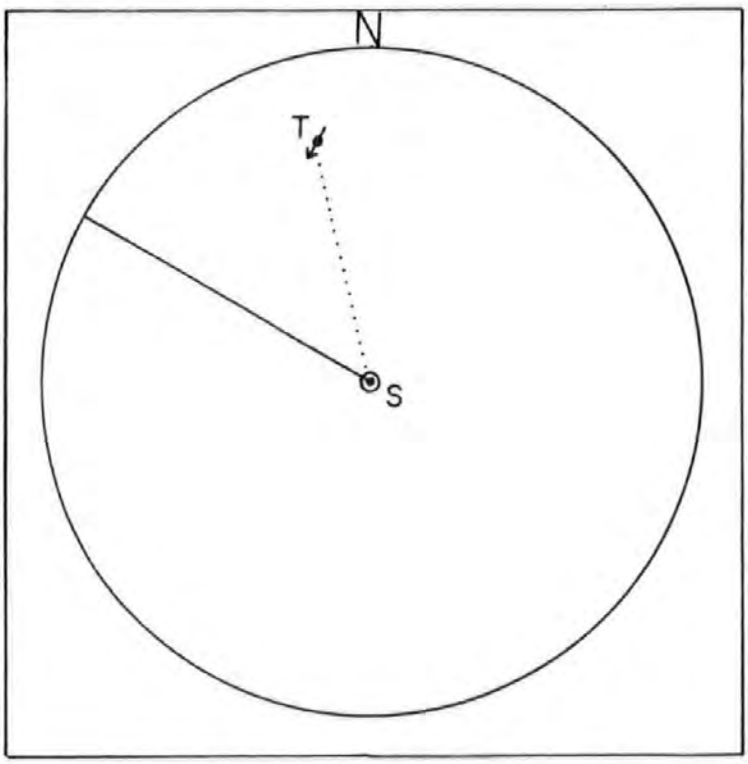
T - Target

S - Own-ship

O - Radar centre

N - North marker

Fig. 9.2 Graphical representation of the P.P.I. in True Motion mode



T - Target

S - Own-ship

O - Radar centre

N - North marker

Fig. 9.3 Graphical representation of the P.P.I. in Relative Motion North-up mode and deleting, which for 36 figures would have taken a great deal of time;

c) Position The exercise was stated as taking place in the Dover Strait and since it was decided that the updating of land was too costly in terms of time, a manner of determining ones position in the area was required. This was achieved by providing the mariner with a small photo-copied chart of the area, with a super-imposed grid. On request the mariner was provided with the position as an x-y co-ordinate. This was thought not to be too unrealistic as frequently at sea a mariner is provided with a Decca fix, in order to determine his position;

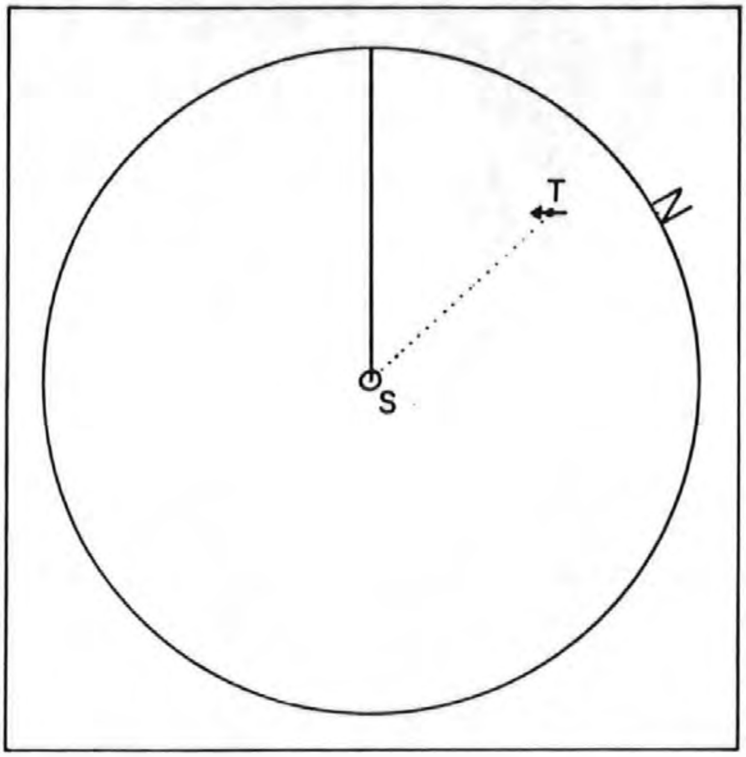
d) Range rings Range rings were provided as an option if demanded. It was found that a vessel passing over a range ring deleted a small section of it, and it was necessary, as a result, for the operator to redraw periodically the range rings.

Plate 9.1 shows a view of the graphical representation of the simulation.

9.2.4 Means of manoeuvring

The fundamental requirement of this model was the facility to allow the mariner to manoeuvre his vessel when and in the manner demanded. Clearly a means of altering the course and/or speed of his own-ship was necessary.

It was decided that the procedure to be implemented for a change of



T - Target

S - Own-ship

O - Radar centre

N - North marker

Fig. 9.4 Graphical representation of the P.P.I. in

in Relative Motion Ship's Head-up mode

course would be for the mariner to specify his new desired course and the rate at which he wished to alter as a percentage of the rudder angle. Thus a mariner on a course of 240 degrees wishing to make a sharp course alteration to starboard onto a new bearing of 300 degrees might specify 300 degrees with 100% rudder angle. An approximation of the rate of turn being equal to the angle of rudder was assumed. A mariner wishing to extend his manoeuvre before the initial command had been completed, simply demanded a new desired course and rate of alteration, resulting in the old specifications being discarded. The model was programmed to always alter course to the new desired bearing in the shortest direction. This could be over-ridden however by specifying a negative percentage of rudder. Thus in the above example, if the percentage of rudder had been defined as -100%, then the vessel would have altered course to a bearing of 300 degrees by turning to port.

The ability to change speed was implemented as a choice of full speed, full manoeuvring speed, slow and dead-slow. The rate of deceleration was a function of which speed range the mariner chose and was constant throughout the manoeuvre.

9.2.5 Target's aspect

One of the restrictions that was placed originally on the computer model was that it represented mariners' actions in good visibility. This was because most of the available data sources were of good visibility and because the Collision Regulations apply a different

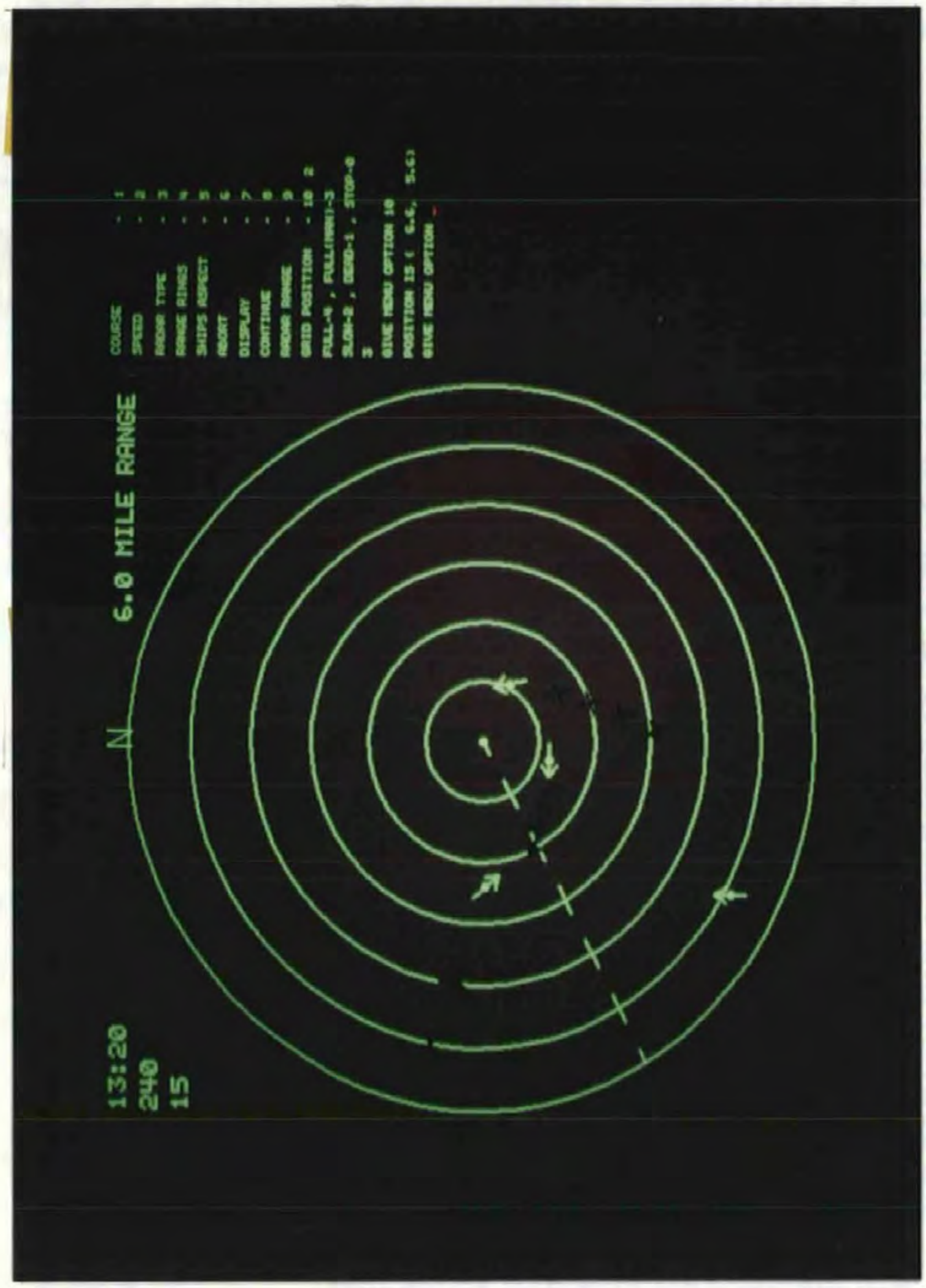


Plate 9.1 The graphical representation of the simulation

code of conduct for collision avoidance in bad visibility. This restriction placed suspicion on simulator results, which through their lack of aspect data, were defined to be in bad visibility. Clearly if the mariner was to make a valid assessment of the model then, since the model was operating under good visibility rules, the requirement for the mariner to be able to navigate under good visibility conditions was of paramount importance.

It was decided that the single most valuable contribution of the visible information assessed by the mariner was that of the target's aspect. To quote Curtis (1980):

> "Aspect is particularly important. In good visibility it gives an early warning of course alteration. A ship can be seen to swing even before its track alters direction. In fog, plotting on radar, detection of this alteration takes about 3 minutes. This additional reaction time means that a considerable extra track separation must be allowed if there is still to be time to avoid collision should an unexpected manoeuvre occur."

Aspect is of further importance in that it allows an immediate assessment of the difference in courses between the two vessels. Thus a vessel on a relative bearing of 40 degrees can be determined, from the aspect alone to be, in one case, paralleling the own-ships course or in another, crossing and consequently a potential threat.

It was decided, for these reasons, that a means of indicating the aspect of all the targets was a necessity. The uncomplicated use of an arrow, centred on the target, was chosen. In all radar modes this represented the true heading of the target.

9.3 The exercise

It was decided that, with the relatively small sample of possible subjects and the time available, only the one exercise would be used. The construction of the exercise was based on the following aims:

a) to produce two collision avoidance manoeuvres by targets of different type and speed;

b) to test initially the time at which a mariner would attempt to overtake another vessel navigating down the main lane and the subsequent track separation;

c) to force the mariner to manoeuvre out of the main lane. The main constraint on achieving the ideal exercise was the duration of the exercise. The maximum realistic time in which the mariner was expected to maintain interest was thought to be approximately 30 minutes and as such restricted the time available to force the mariner to overtake. One solution would have been to reduce the speed of the overtaken vessel, but this would have resulted in an untypical encounter taking place.

9.4 The experimental procedure

It was decided that the most suitable subjects for the computer simulator exercises were the experienced mariners studying for the degree in Nautical Studies. The reason for this choice, as opposed to the more obvious one of those on professional courses, was that their study included computing and resulted in them having a more flexible attitude to the artificial nature of the computer presentation. A total sample of 18 subjects including 3 master mariners was collected. Each exercise consisted of three sections: the introduction; the exercise and the debriefing.

9.4.1 The introduction

The main aim of the introduction was to put the subject completely at ease. The different radar modes and options available to him were explained, as was the manner by which he manoeuvred and the significance of the arrow on the targets representing the aspect. The subject was actively encouraged to ask any questions or to express any doubts he might have concerning any aspect of the simulation or the exercise. He was given a chinograph pencil, and a flexible rule to make any necessary geometric constructions on the screen. Further minor problems of ergonomics, in particular the orientation of the screen in a vertical as opposed to horizontal plane and the unavoidable parallax were dealt with. The subject was then shown his starting position in the area by a position from the computer, along with his course, speed and ship type.

9.4.2 The exercise

In all of the exercises the operator took full control of the computer under the orders of the mariner. Little help was given to the subject, except in the identification of targets. This was thought to be justified since at sea, under good visibility, the type of vessel would be easily obtained. In most cases the exercise took approximately 30 minutes to complete, being terminated when the mariner was satisfied with his course and speed after having negotiated all possible encounters.

9.4.3 The debriefing

The debriefing was of an informal nature, with a record of the encounter being displayed on the graphics terminal. The mariner was asked to explain his decision making process regarding any collision avoidance or lack of it and to comment on the action of the targets in the simulation, both with respect to his own ship and each other. He was asked also to answer a series of questions concerning the manoeuvres of the two target vessels, which are discussed in detail below. Finally, if forced to manoeuvre out of the routing scheme, the manner in which he came back onto a satisfactory track was investigated.

9.5 The results

9.5.1 Analysis of manoeuvres

The track plots of the individual exercises are shown in Figures 9.5 to 9.22. The sample was too small to attempt a statistical analysis of any significance and consequently the results are treated qualitatively. In each case the mariners were assigned subject numbers. These were not assigned in chronological order, but were grouped by the type of manoeuvre observed to take place. The first 8 subjects, Group A, altered course to starboard after the ferry from Dover (ship 4) had been detected and as a result were regarded as manoeuvring solely for ship 4. Of these, subjects 1,2 and 3 delayed altering course for ship 4 until the overtaken vessel (ship 2), had made its manoeuvre. Subjects 9 to 14, Group B, altered course to starboard to overtake ship 2, making their manoeuvre before ship 4 had been detected. Subject 15, Group C, prefered not to alter course to starboard, and reduced speed to "slow" immediately after ship 2 had manoeuvred. The final group, Group D, subjects 16,17 and 18 all followed the unorthodox procedure of altering course to starboard. In all three cases the port manoeuvre was in good time and in only one example, subject 17, was it dangerous.

9.5.1.1 Group A

This group consisted of two distinct sets of mariners. The first whose main objective was to leave room for ship 2 to manoeuvre to starboard if it required and the second whose principle aim was to stay inside the main lane at all costs. In all cases where the mariner altered out of the main lane, some attempt was made to return. It was of interest to note that those who attempted to get back into the lane the quickest (subjects 1,2 and 3) were the ones who had delayed altering initially until ship 2 had manoeuvred. The observation was made by those delaying alteration that once the ferry bound for Dover (ship 3) had manoeuvred, an immediate manoeuvre to starboard would to some degree have cancelled its effectiveness, hence the reason for further delaying their own alteration.

9.5.1.2 Group B

Group B consisted of those mariners who made an early decision to alter course for ship 2, and attempt to increase the track separation. In all six cases the over-riding factor in their decision was the desire to leave manoeuvring room to starboard. Subjects 9, 10 and 11 had no reservations about entering the E.I.T.Z. and as a consequence took broad alterations. Subjects 9 and 10 altered sufficiently to cancel the need for a further alteration to avoid the ferry from Dover, ship 4 and the altering ship 2. Subject 11, however was not satisfied with the resulting C.P.A. of 3 cables with ship 2 and felt forced to make a further alteration to starboard. Subjects 12,13 and 14 manoeuvred, in all three cases, at approximately 3 minutes into the "run", so as to overtake ship 2 to starboard. It was interesting to note that none of these subjects manoeuvred to starboard for ship 4. All three subjects expressed a reluctance to manoeuvre out of the main lane and consequently slowed down. Subject 13 slowed down to 3 knots so early that ship 3 was not required to make any alteration.

9.5.1.3 Group C

It was noticed that the master mariners were the most cautious of all the subjects. This is illustrated in Group C, containing just the one subject, 15. Showing a reluctance to alter course to port or to manoeuvre into the E.I.T.Z. he simply reduced speed to slow at minutes before C.P.A.. The other master mariner, subject 13, also displayed the same reluctance.

9.5.1.4 Group D

The pertinent feature about Group D was that two out of three of the mariners were used to navigating large tankers. This was relevant because the deep water route often used by V.L.C.C.s passes south of the Varne. Indeed in the debriefing both ex-tanker mariners, subjects 16 and 18 considered their manoeuvres navigation as opposed to collision avoidance alterations. This was clearly justified by subject 18 who manoeuvred early enough to eliminate the requirement for ship 3 to alter course. Subject 16, however, did not start to alter course until 6 minutes before C.P.A., and it was therefore regarded as a collision avoidance manoeuvre. Subject 17 illustrated perfectly the danger of not leaving sea-room to starboard. His final manoeuvre to starboard at 20 minutes was an attempt to bring his stern around at the last minute.

9.5.2 Actions of the target ships

The first criticism concerning the action of the targets was about the manoeuvre by ship 3 to avoid ship 1. Subject 5, mentioned that the ferry had made too small an alteration of course and that he had not been convinced that the ship was in fact attempting to make a C.A.M.. On further research (3.3) it was observed that mariners tended to alter course to a bearing to pass astern of the target. This change was made to the model. A further criticism was made of the action taken by ship 2, saying that

> "in practice a vessel would communicate his intentions by V.H.F., and if no response could be obtained, would slow-down as opposed to a sudden alteration of course to starbaord.".

It was noted, however from the radar film observations that in practice mariners frequently suprised other traffic by such action.

Table 9.1 shows the mariners' reactions towards the realistic nature of the alteration of ship 3 and Table 9.2 illustrates their reactions to ship 2's manoeuvre to ship 4. It can be seen that 78% of the mariners thought that the manoeuvre by the Dover bound ferry was realistic or reasonable. In this situation realistic was defined as representing the usual response, whilst reasonable represented a common-place manoeuvre. It is notable that the only mariner to give a score of less than 3 was the first subject, and the one who commented on the magnitude of the initial course alteration.

On considering the manoeuvre in greater detail the sample was reduced by those mariners who through altering course at an early stage in the exercise, had eliminated the need for the ferry (ship 3) to alter course (represented by an "*" in the relevant column). Out of the 14 subjects that observed the ferry altering, however: 50% regarded the time of alteration (R.D.R.R. = 6 minutes) to be as was expected; 29% thought the ferry altered course too early and 21% felt it was too late in altering. 50% of the subjects considered the magnitude of the manoeuvre to be as expected, 29% thought it was too great and 21% that it was too small. 64% regarded the time of altering back on to course to be correct, 14% that it was too late and 21% that it was too early. A large proportion of the subjects that considered it to be too early, expressed the opinion that a ferry was unlikely to be so generous in practice.

In the case of the slow, 8 knot main lane vessel (ship 2) being forced to give-way to the ferry from Dover (ship 4): 39% considered the manoeuvre to be realistic; 39% thought it was reasonable and 22% felt it was possible. Of those giving a score of 2 or less, the main criticism concerned the lack of warning by ship 2 that a manoeuvre was about to take place. It was mentioned that at sea, in a situation where a manoeuvre might force a previously unthreatened vessel to alter course, that an attempt by the mariner about to manoeuvre would be made to communicate his intent to that vessel. 67% of the mariners thought the vessel manoueuvred at a realistic time, 28% thought it was too late and 5% thought it was too early. 78% considered that the magnitude of the manoeuvre was realistic and 22% that it was too great. 72% regarded the time of altering-back to be correct, 11% thought it was too late and 17% thought it was too early.

9.5.3 Routing Scheme boundary

The sample of mariners was too small to consider how mariners attempted to get back into the T.S.S.. The debriefing however revealed three distinct schools of thought. The first were those that on seeing no other vessels in the vicinity made no attempt to return to the main lane. The second were those that followed Rule 10 precisely and attempted to return to the main lane at as narrow an angle as possible. The third consisted of those that considered any time spent in the E.I.T.Z. to be hazardous and hence returned as quickly as possible. It was of interest to note that the third group comprised mainly those who had avoided altering out of the scheme until the very last minute.

78% of the subjects, on completing the manoeuvre to ship 4, switched up to the 12 mile range on the radar. The majority of the mariners who made an attempt to return to the T.S.S. made use of the Varne light-vessel to determine the required course.

9.6 Overall assessment

It must be concluded that the exercise was successful as a means of demonstrating the behaviour of the computer simulation to professional seamen. In general the participants forgot quickly the artificiality of the situation, and became involved in the plotting and assessment of changing situation. The majority of the mariners could recount all the relevant encounters that took place without the aid of the subsequent track plot. In several of the cases it was mentioned that once ship 3 had been observed to alter course to clear the mariner driven vessel that it was no longer considered, in these cases the use of the track plot as a reminder proved invaluable.

The results have shown, in both situations, that the majority of mariners considered the ships' behaviour to be as would have been expected at sea. It has further been shown that the manoeuvre parameters determined from the radar film were justified.

Table 9.1 The manoeuvre by ship 3 to avoid the mariner driven vessel

Subject	Overall manoeuvre assessment	Time of manoeuvre	Magnitude of manoeuvre	Time of alter-back
1	3	-	+	+
2	2	-	-	-
3	3	+	+	=
4	1	=	=	-
5	4	=	-	=
6	1	=	=	=
7	2	+	+	-
8	1	-	=	=
9	1	*	*	*
10	2	*	*	*
11	2	=	=	=
12	1	=	=	+
13	1	*	*	*
14	3	+	+	=
15	1	*	*	*
16	2	=	=	=
17	2	+	-	=
18	1	*	*	*

Key.

Overall manoeuvre assessment:
- 1 - realistic;
- 2 - reasonable;
- 3 - possible;
- 4 - unlikely;
- 5 - unrealistic.

Time of manoeuvre and time of alter-back:
- "+" - late manoeuvre;
- "=" - as expected;
- "-" - early manoeuvre;
- "*" - no information available.

Magnitude of manoeuvre:
- "+" - too great;
- "=" - as expected;
- "-" - too small;
- "*" - no information available.

Table 9.2 The manoeuvre by ship 2 to avoid ship 4

Subject	Overall manoeuvre assessment	Time of manoeuvre	Magnitude of manoeuvre	Time of alter-back
1	2	=	=	=
2	3	=	=	=
3	3	-	+	=
4	2	+	=	-
5	3	+	=	=
6	2	=	=	=
7	1	=	=	+
8	2	=	=	=
9	3	+	+	=
10	1	=	=	=
11	2	=	=	+
12	1	=	=	-
13	2	+	+	=
14	1	=	=	=
15	1	=	=	=
16	1	=	=	=
17	1	=	=	=
18	2	+	+	-

Key.

Overall manoeuvre assessment:
- 1 - realistic;
- 2 - reasonable;
- 3 - possible;
- 4 - unlikely;
- 5 - unrealistic.

Time of manoeuvre and time of alter-back:
- "+" - late manoeuvre;
- "=" - as expected;
- "-" - early manoeuvre;
- "*" - no information available.

Magnitude of manoeuvre:
- "+" - too great;
- "=" - as expected;
- "-" - too small;
- "*" - no information available.

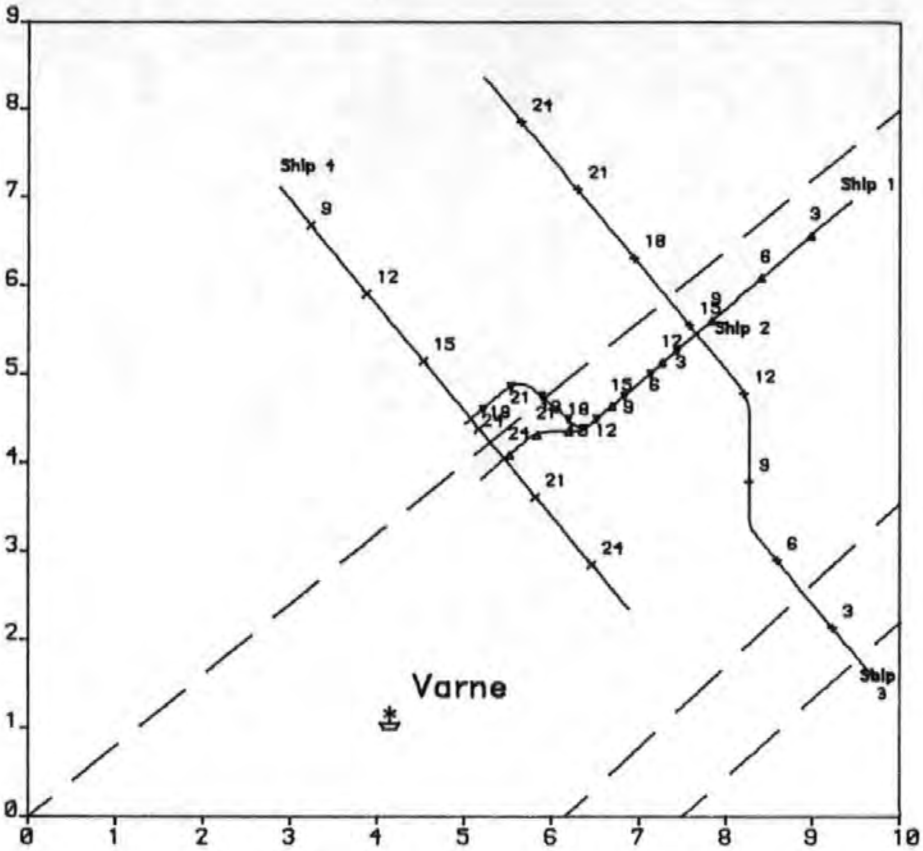


Figure 9.5 Subject 1

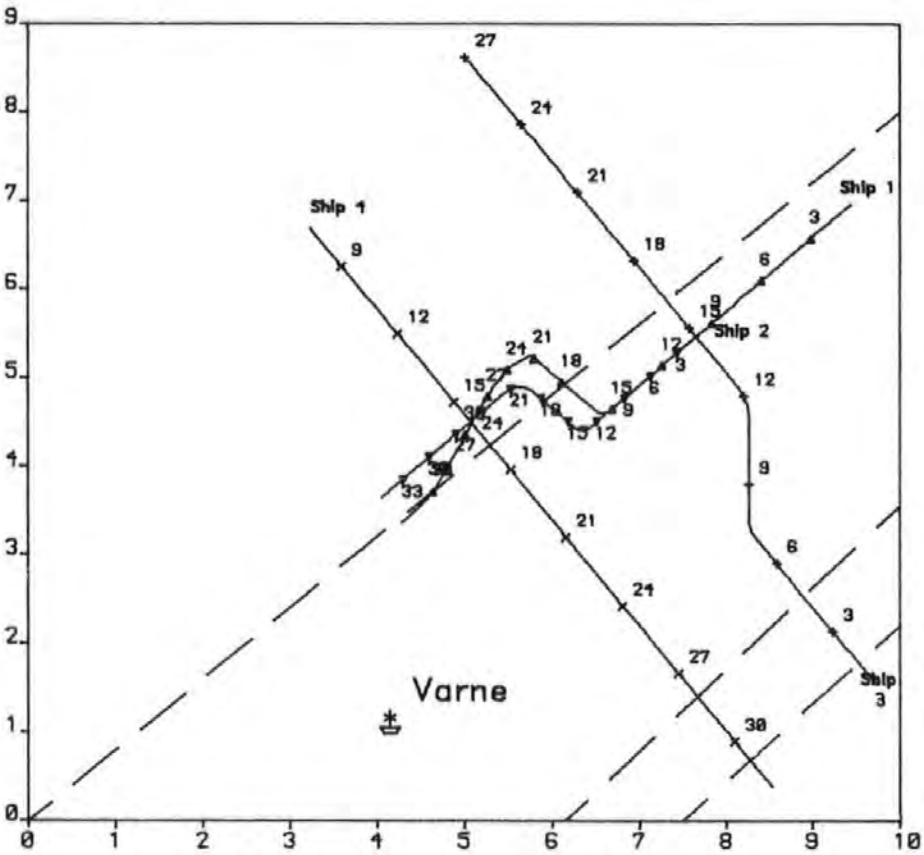


Figure 9.6 Subject 2

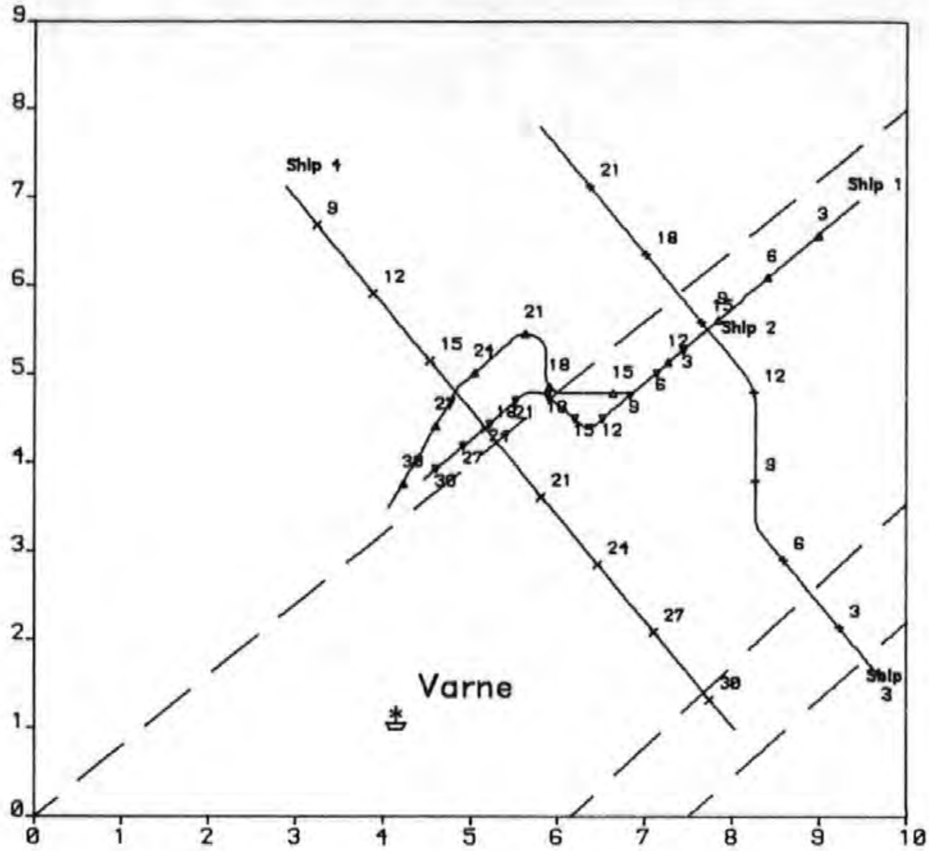


Figure 9.7 Subject 3

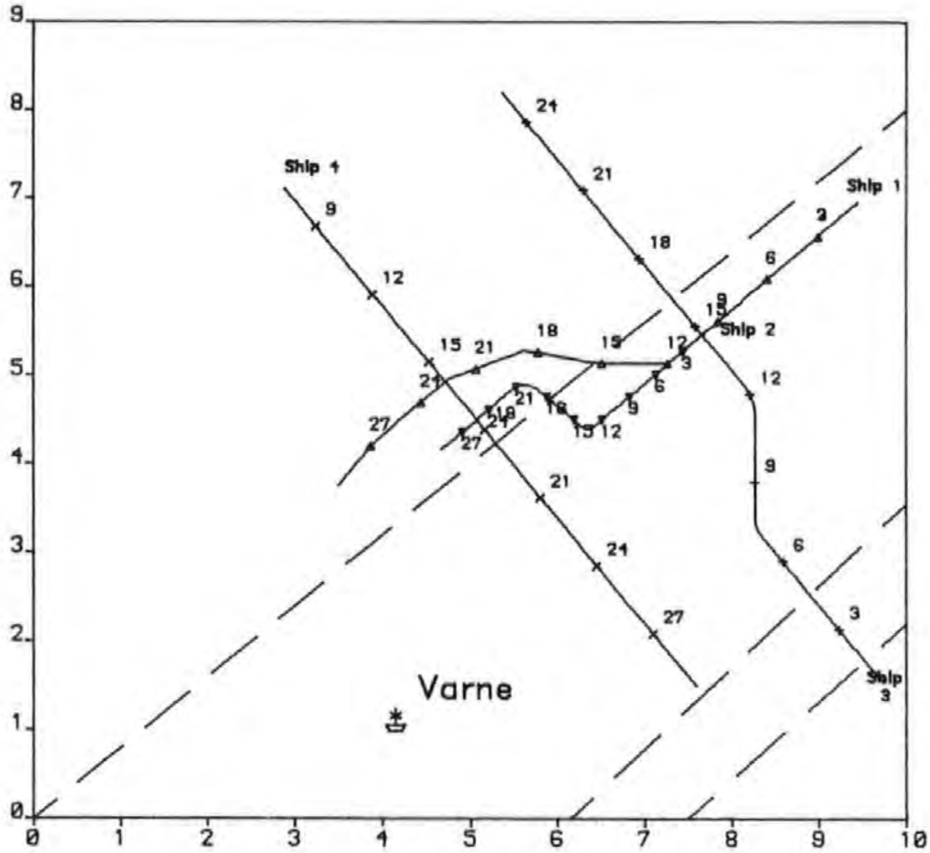


Figure 9.8 Subject 4

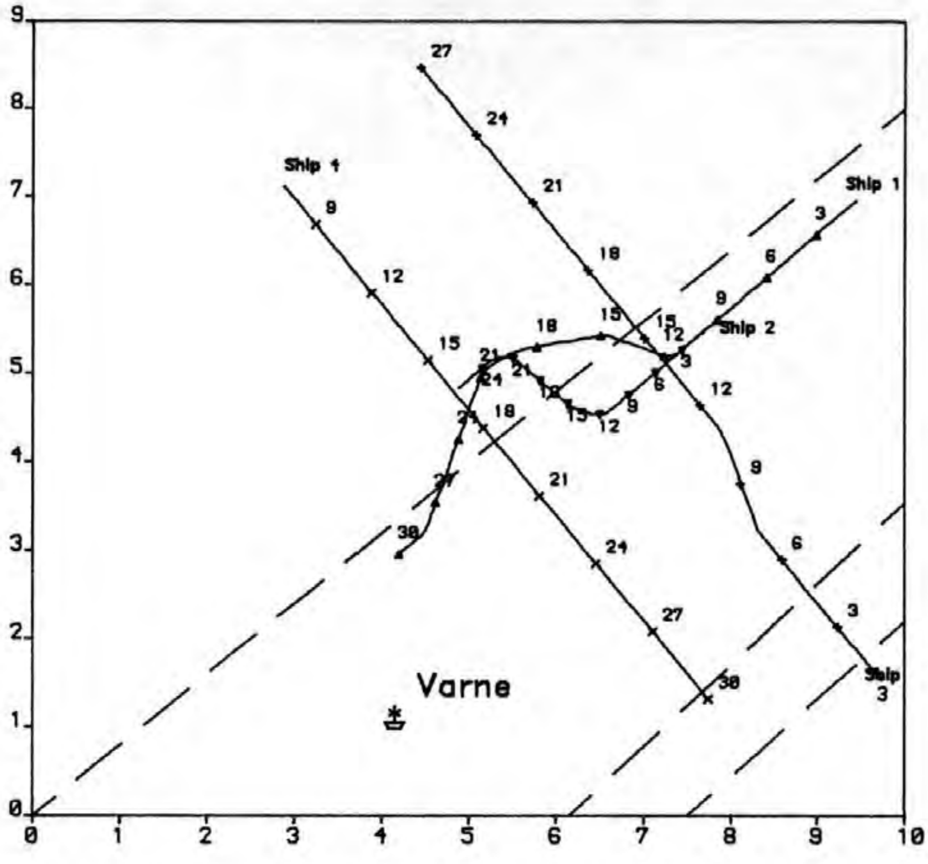


Figure 9.9 Subject 5

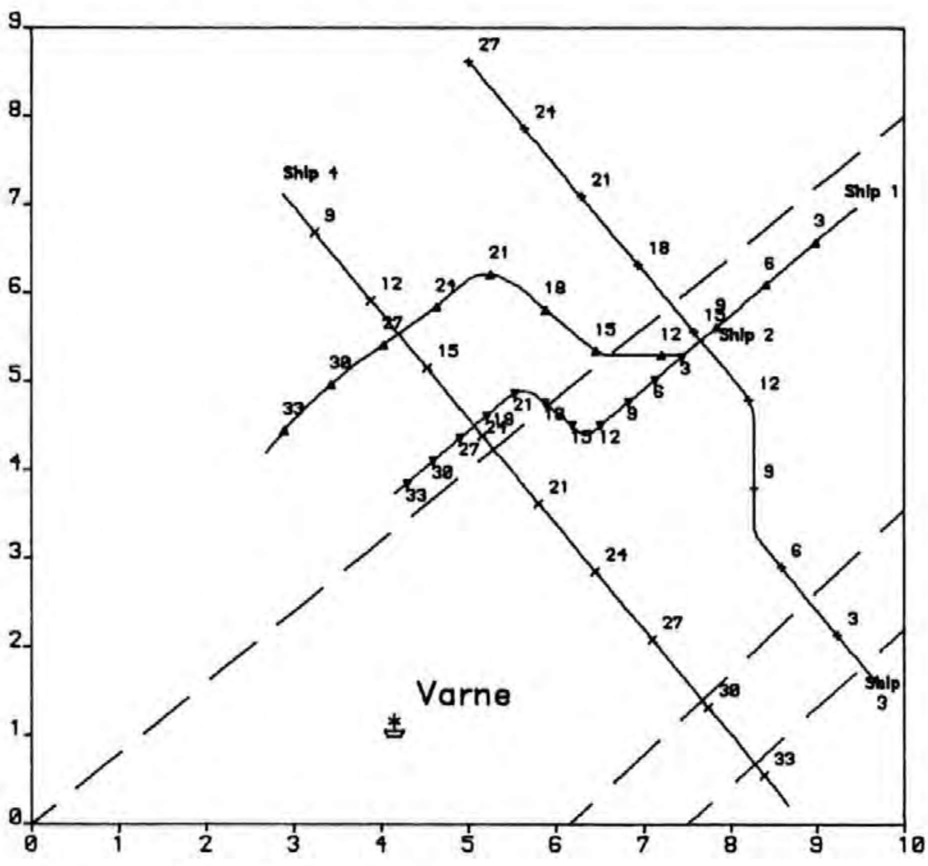


Figure 9.10 Subject 6

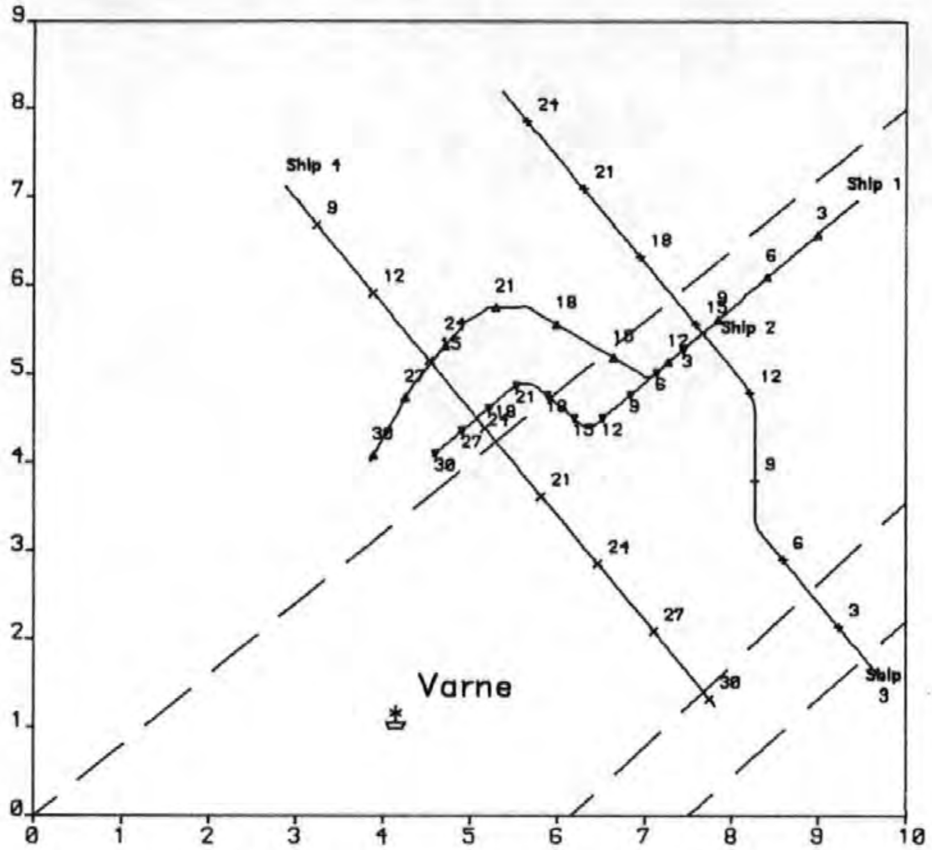


Figure 9.11 Subject 7

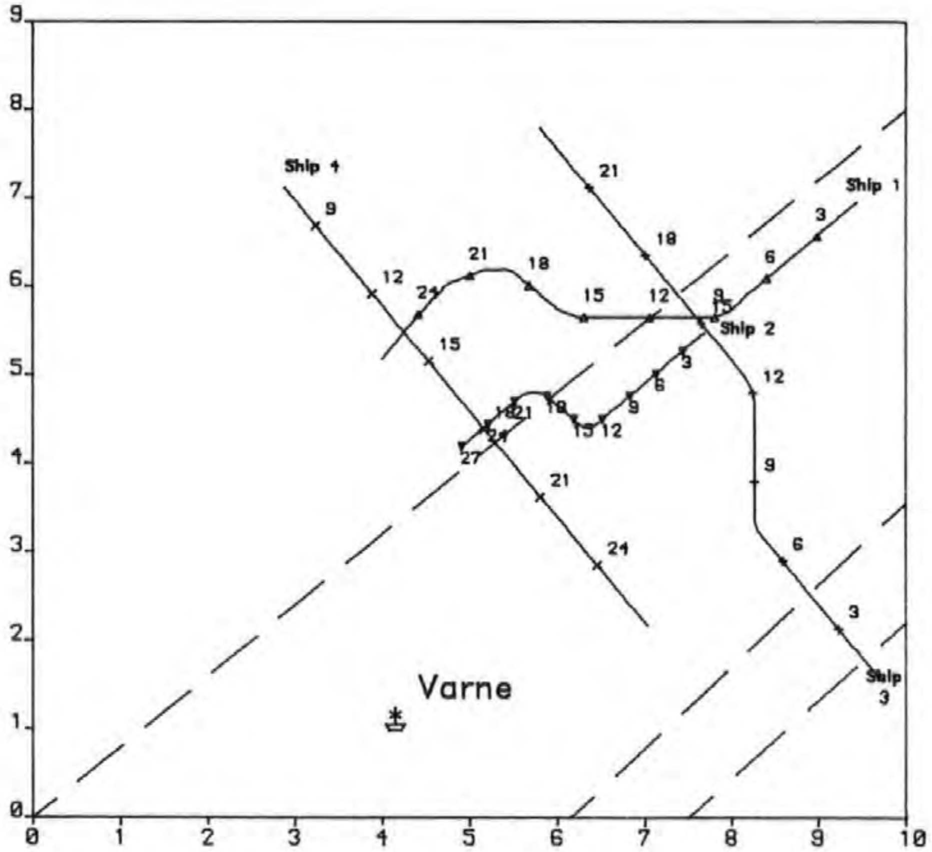


Figure 9.12 Subject 8

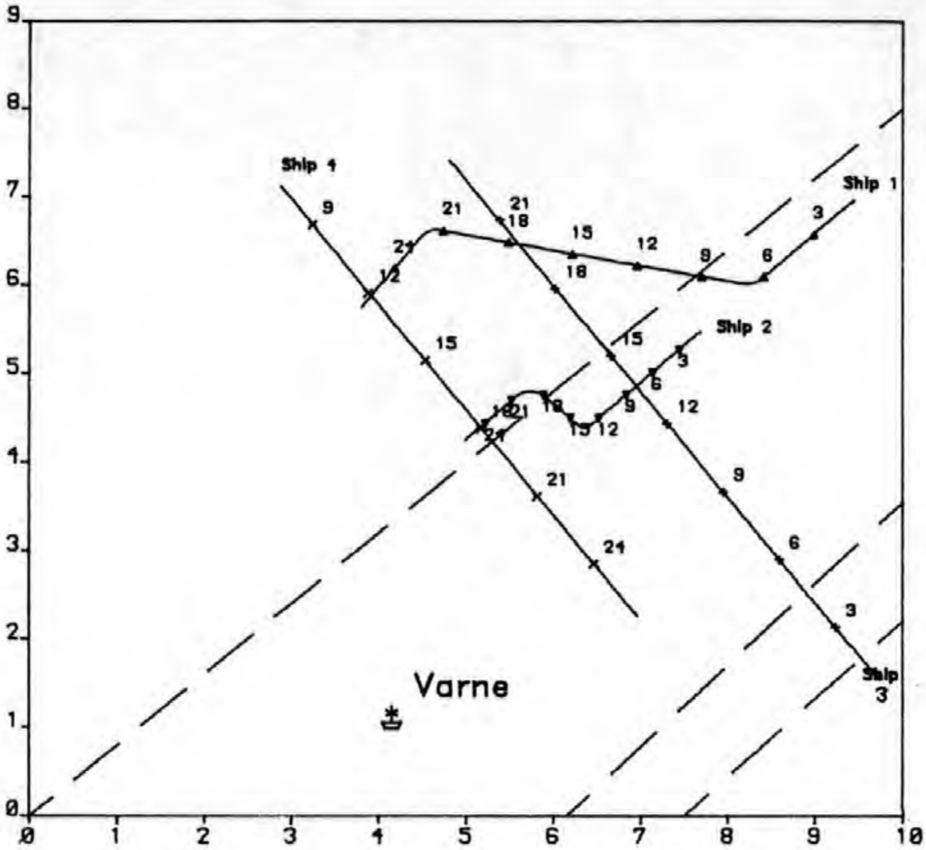


Figure 9.13 Subject 9

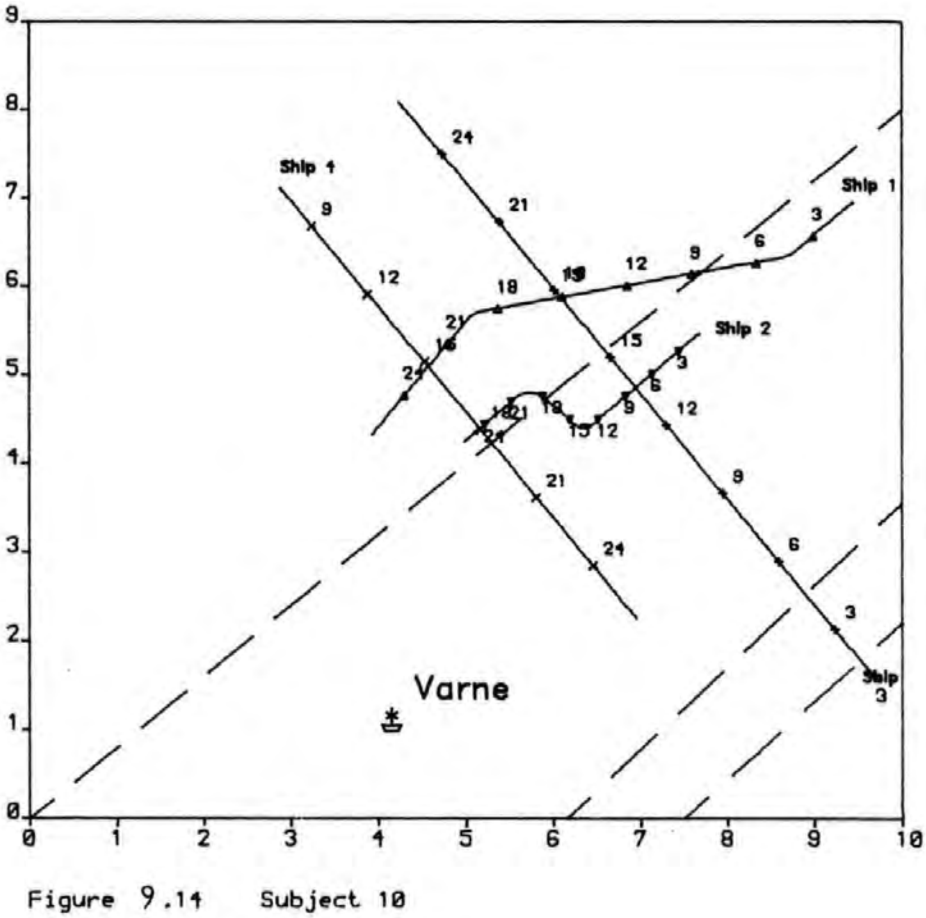


Figure 9.14 Subject 10

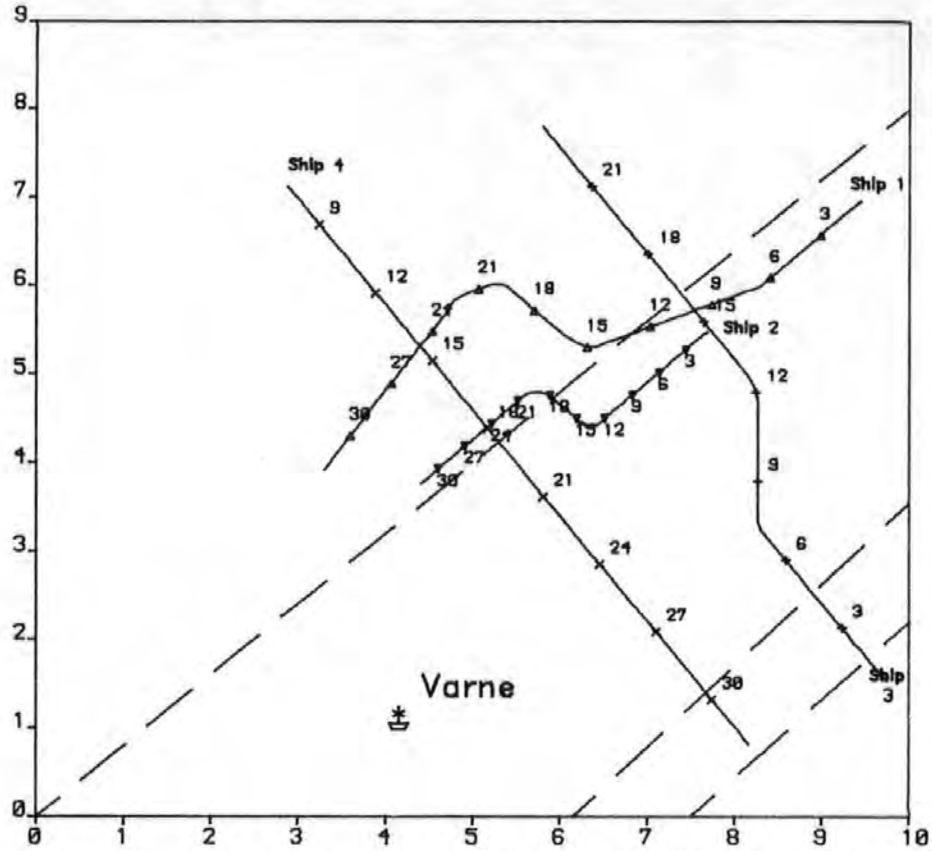


Figure 9.15 Subject 11

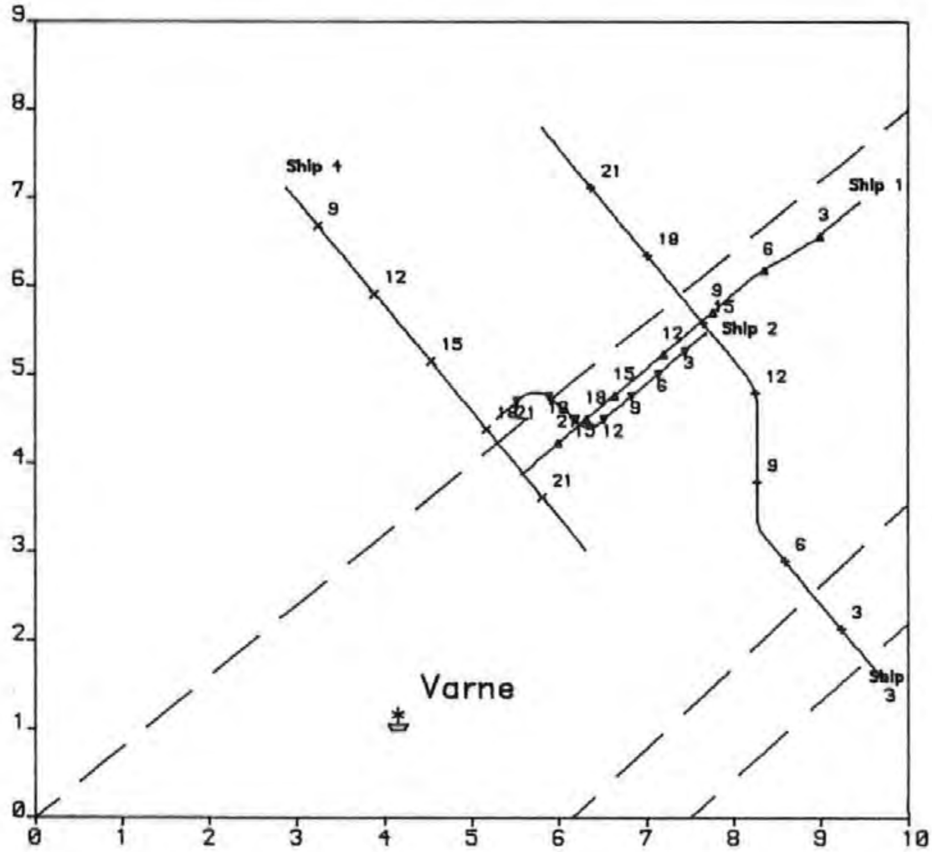


Figure 9.16 Subject 12

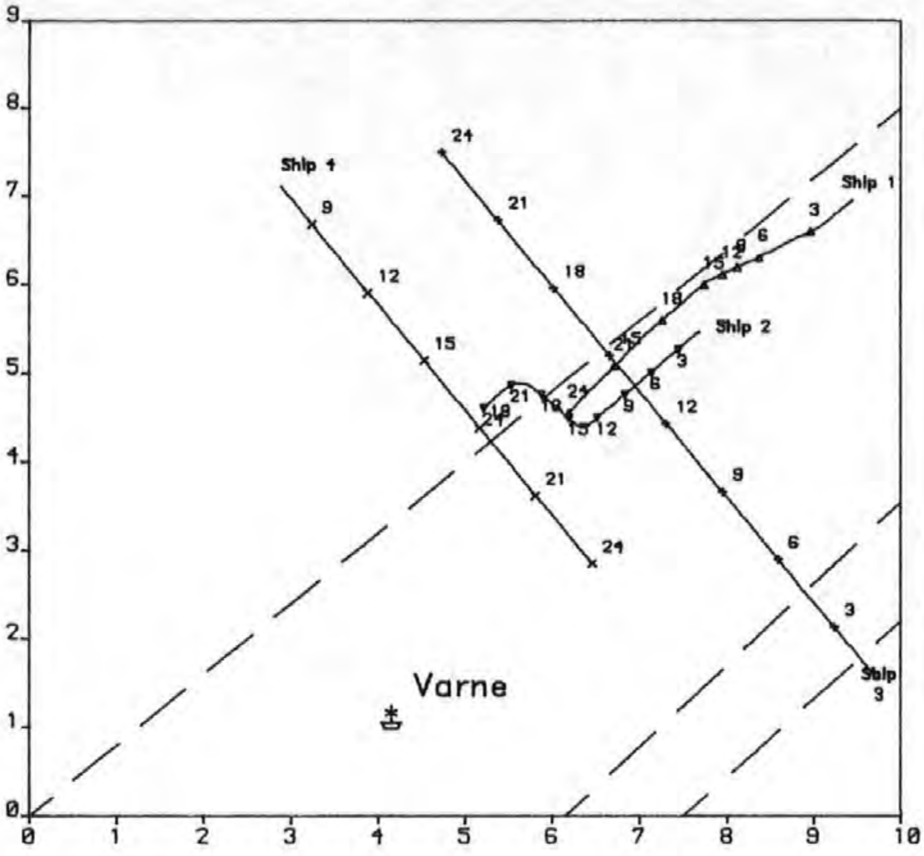


Figure 9 .17 Subject 13

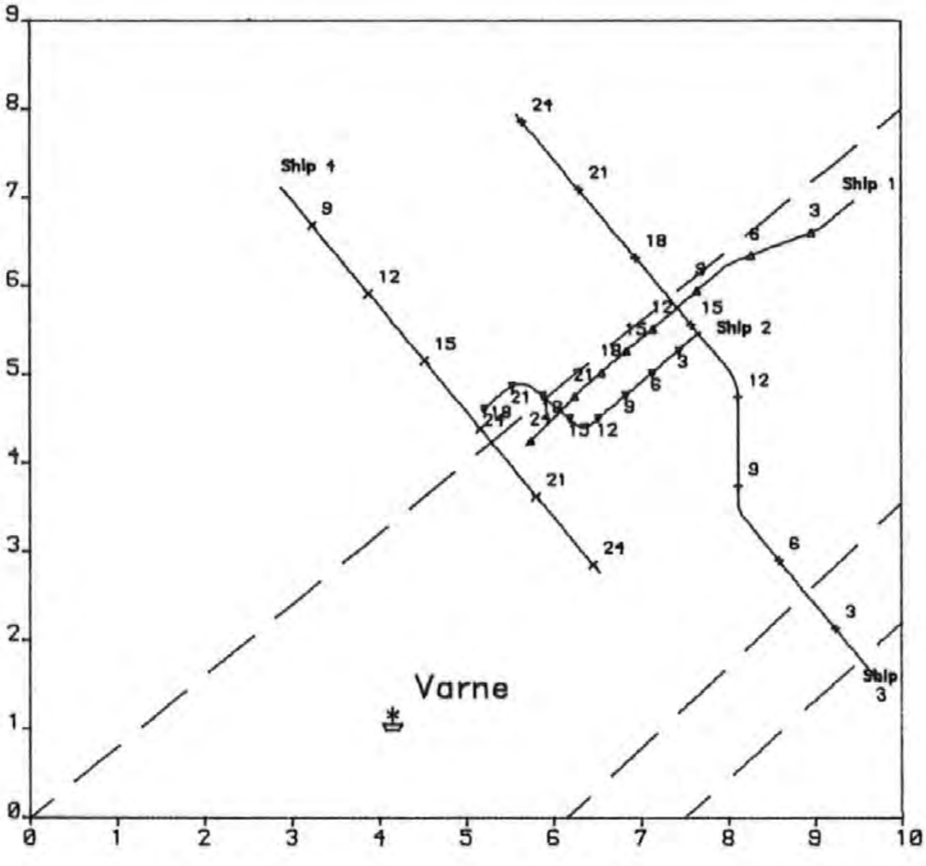


Figure 9 .18 Subject 14

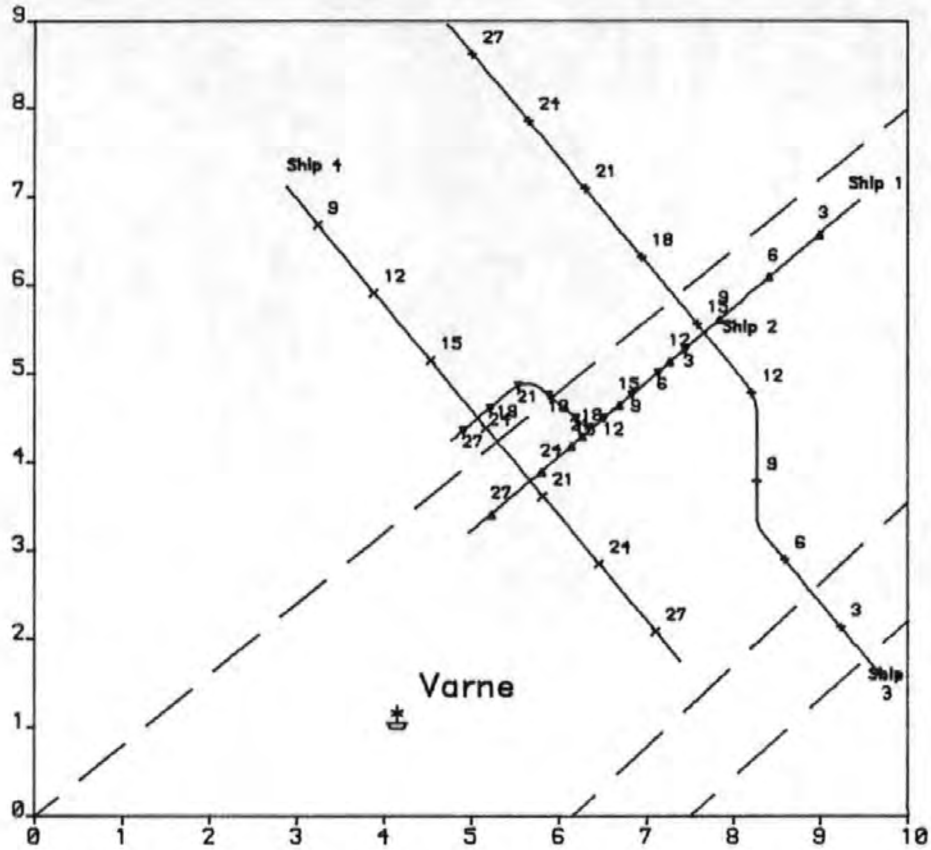


Figure 9.19 Subject 15

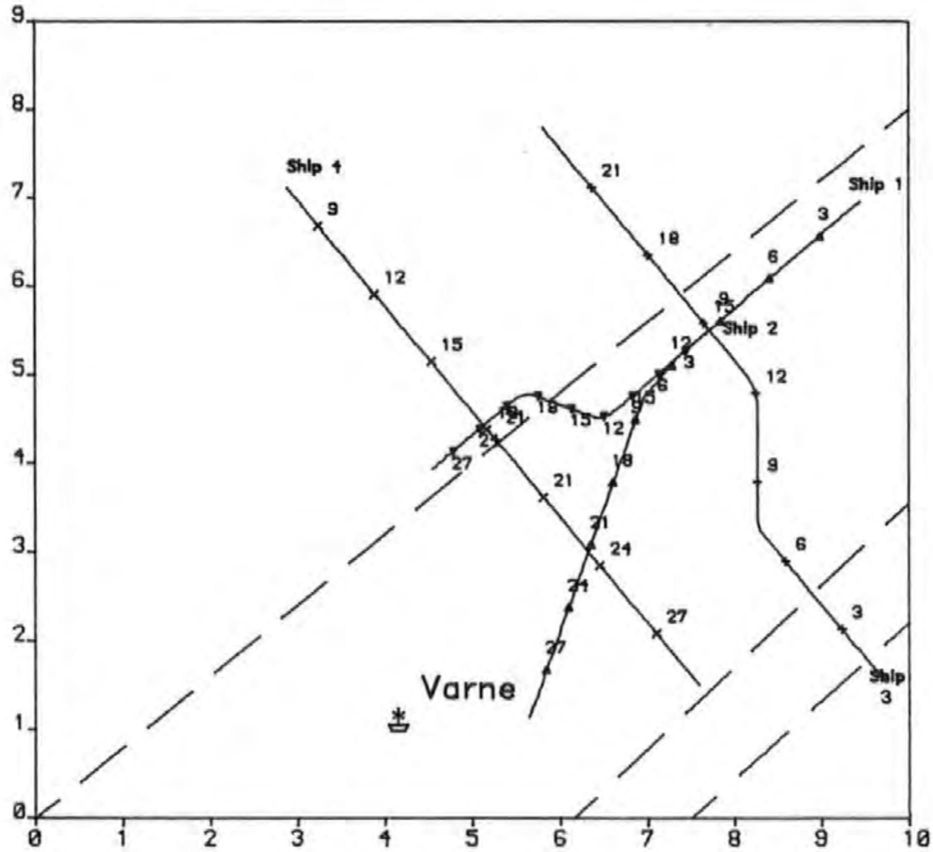


Figure 9.20 Subject 16

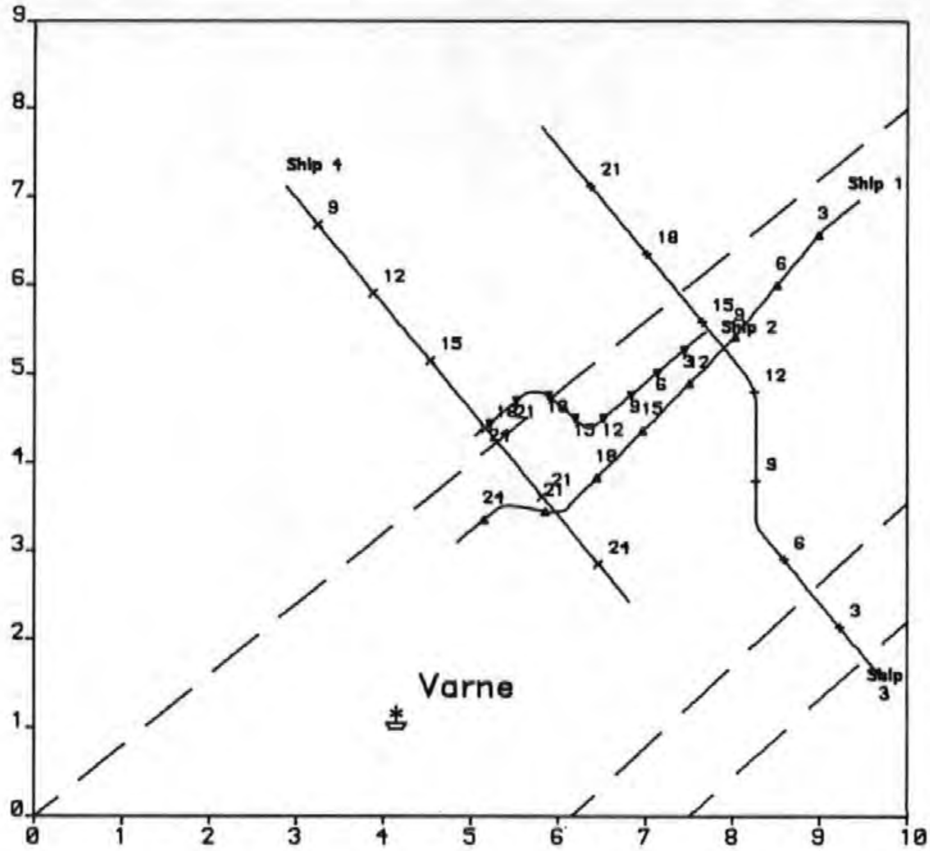


Figure 9.21 Subject 17

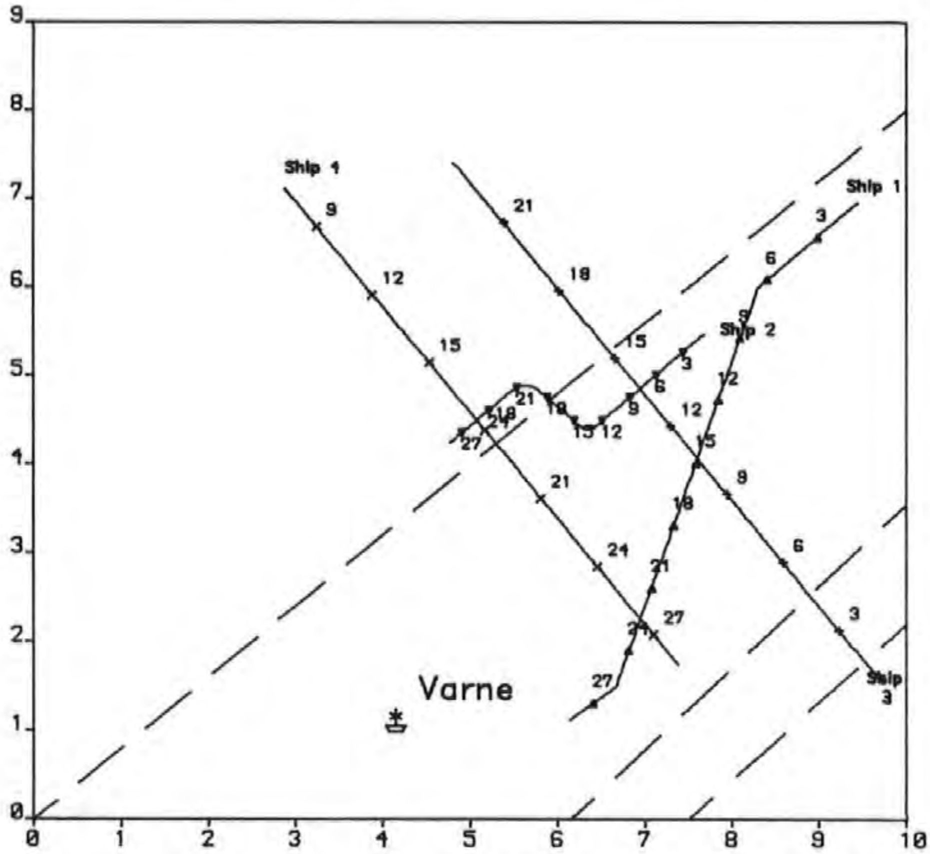


Figure 9.22 Subject 18

Chapter 10 Conclusions

A demonstration has been given of the way in which ships' manoeuvres may be simulated realistically with a computer by the use of a mathematical model employing the concept of circular domains and the R.D.R.R. criterion. A selection of two ship encounters have been demonstrated along with examples of the way in which the method can cope with the less frequent three and multi-ship encounters.

The R.D.R.R./domain manoeuvring model has been used as the basic building block of a computer simulation of a 19 n.mile long section of the main westbound traffic lane in the Dover Strait. Crossing traffic and the adjacent inshore traffic zone have been included. Buoys are implemented as stationary targets and depth contours as set of limiting courses in the direction grid. In this manner over 400 vessels over two days of continuous traffic were simulated for data derived directly from historical data and for data generated from pre-determined statistical distributions, under good visibility conditions. These were then carefully validated against the observed data over the same two days.

The simulation represents a significant advancement on previous research work which did not have the facility for ships to manoeuvre out of collision situations, the ships continued on preset tracks. The area simulation allows ships to make collision avoidance manoeuvres. It therefore enables the effect on the traffic flow pattern of these manoeuvres to be studied. In particular the use of the model as a decision support system has been demonstrated in several important situations. It has been utilized in the observation of the effect of rogues, both manoeuvring and standing-on, directly against the main traffic flow. The more subtle effect of ferries not crossing at right angles was also considered. Both the above two uses of the simulation might now be considered redundant as the numbers of vessels not following the Collision Regulations, as applied to the T.S.S.s, has clearly fallen over recent years.

A more useful function of the model, in its predictive role, is in considering the effect of possible future developments both expected and unexpected. For this reason the effect of a large obstruction partially blocking the traffic flow was considered. The large obstruction could be a slow moving tunnelling device protected by marker vessels. It might be the installation of an oil-drilling rig. Whatever its guise the advantages of a system able to make an accurate forecast of the effects on traffic flow and then capable of comparing different means of controlling the traffic flow are obvious.

The model has also the ability to make a quantitative assessment of the effects of a sudden increase in traffic density, which although the recession has resulted in a slight reduction in the number of vessels navigating through the Dover Strait, might be of use in the future. Conversely the possibility of reducing constraints on the traffic flow given a decrease in traffic density is also easily considered.

It is well recognized that the Dover Strait is one of the most heavily trafficked areas of sea in the world, but the basic principles by which the model was constructed are just as valuable in any other water-way, since all follow the International Rules for Preventing Collision at Sea. The means of determining the different parameters have been demonstrated and should be universally applicable, whether in the Mallacca Straits or the Straits of Gibraltar.

The development of the computer controlled radar simulation was developed initially to consider the realistic behaviour of the simulation. The philosophy of this departure from the initial method of simply presenting mariners with examples of generated plots was to increase the mariner participation and reduce the artificial nature of the former method. It proved however to be one of the most practical uses of the simulation model. Although only applied on a computer graphics terminal, the same basic logic used to control the target vessels could be equally applied to the target vessels on a radar simulator. This would facilitate the objective assessment of students undertaking a radar simulator course, as all judgements concerning the type of action necessary would be following the same framework of rules.

It has been shown that by considering a shipping system as two main components comprising the manoeuvring and the navigation logic, a realistic simulation of two days continuous traffic can be generated for a physical area of sea. It has been shown how the model was validated by comparing results inherent to the system against those simulated by the computer model.

<u>Future developments</u> Proposals have been put forward by Plymouth Polytechnic to undertake research towards a marine guidance, integrated navigation and hazard avoidance system. The aim being to combine a recently developed estimator/controller for the navigation and guidance of large ships with the model developed through the course of this research to automatically navigate and manoeuvre when necessary a vessel. If successful this would represent a significant step towards a fully automated vessel. It is feasible that such a system might one day become a common feature in the shipping industry, although it is the author's opinion that it will act solely as a decision support and automatic alarm system to the irreplacable mariner.

References

Abdelgalil, E.M. (1978) Shipping Casualties and Ship's Domains. Marine Traffic Service - Proceedings of the Third International Symposium, Liverpool. pp95-107.

Barratt, M.J. (1973) Encounter Rates in a Marine Traffic System. Journal of Navigation. Volume 26, pp458-465.

Barratt, M.J. (1980) Collision Avoidance as Observed by Shore Based Radar. Journal of Navigation. Volume 33, pp339-350.

Barratt, M.J. and Hewson, C.M.T. (1974) Ship Encounters and Flow in Selected Areas of the Dover Strait. N.P.L. report. Mar-Sci R117 Sept. 1974.

Batkin, R.J. (1976) The study and analysis of interactions between vessels in traffic routing systems by digital simulation modelling. M.Phil. Thesis C.N.A.A. Oct. 1976.

Brough, J. and Jones, K.D. (1970) An Investigation into the Use of Radar for Collision Avoidance. Journal of Navigation. Volume 23, pp87-98.

Bury, J.E. (1977) The Practical Background: Setting the Scene. Institute of Mathematics and its Applications. Conference on Mathematical Aspects of Marine Traffic. pp19-22. Published 1979 by Academic Press.

Cahill, R.A. (1983) Collisions and their Causes. Published 1983 by Fairplay Publications.

Calvert, E.S. (1960) Manoeuvres to Ensure the Avoidance of Collision. Journal of Navigation. Volume 13, pp127-137.

Calvert, E.S. (1967) Collision Avoidance by Manoeuvre.
Journal of Navigation. Volume 24, pp413-417.

Calvert, D.I. (1983) A New Characterisation of the Centre of a Circle.
Internal Publication. Plymouth Polytechnic.

Cockcroft, A.N. (1977) Statistics of Ship's Collisions.
Journal of Navigation. Volume 31, pp216-225.

Cockcroft, A.N. (1981) The Circumstances of Sea Collisions.
Symposium on Vessel Traffic Services. Bremen, April 1981.

Cockcroft, A.N. (1983) The Effectiveness of Ship Routing off North-West Europe. Journal of Navigation. Volume 36, pp462-467.

Cockcroft, A.N. and Lameiger, J. (1982) A Guide to the Collision Avoidance Rules. London: Stanford Maritime Press.

Coldwell, T.G. (1983) Marine Traffic Behaviour in Retricted Waters.
Journal of Navigation. Volume 36, pp430-444.

Colley, B.A., Curtis, R.G. and Stockel, C.T. (1983) Manoeuvring Times, Domains and Arenas. Journal of Navigation. Volume 36, p324-328.

Colley, B.A., Curtis, R.G. and Stockel, C.T. (1984) On Marine Traffic Flow and Collision Avoidance Computer Simulation.
Journal of Navigation. Volume 37, pp232-250.

Curtis, R.G. (1977) An Analysis of the Danger of Ships Overtaking.
Institute of Mathematics and its Applications.
Conference on Mathematical Aspects of Marine Traffic. pp175-191.
Published 1979 by Academic Press.

Curtis, R.G. (1978) Determination of Mariner's Reaction Times.
Journal of Navigation. Volume 31, p408-417.

Curtis, R.G. (1980) The Probability of Close Overtaking in Fog.
Journal of Navigation. Volume 33, p329-340.

Davis, P.V. (1981) Computer Modelling of Marine Traffic Behaviour. PhD Thesis. CNAA.

Davis, P.V. (1981) Validation of Radar Simulation Results by Comparision with Observation of Overtaking Manoeuvres at Sea. Forum Article. Journal of Navigation. Volume 34, pp471-473.

Davis, P.V., Dove, M.J. and Stockel, C.T. (1980) A Computer Simulation of Marine Traffic using Domains and Arenas. Journal of Navigation. Volume 33, p215-222.

Degré, T. and Lefèvre, X. (1978) A Simulation Model of Marine Traffic in the Dover Strait. Marine Traffic Services - Proceedings of the Third International Symposium, Liverpool. pp117-130.

Degré, T. and Lefèvre, X. (1981) The manoeuvring room concept - Applications to Collision Avoidance Problems. Symposium on Vessel Traffic Services. Bremen, Volume 2. pp144-162.

Degré, T. and Lefèvre, X. (1983) Collision Avoidance from the Shore. Journal of Navigation. Volume 36, pp411-417.

Draper, J. and Bennett, C. (1972) Modelling Encounter Rates in Marine Traffic Flows in Particular Application to the Dover Strait. Journal of Navigation. Volume 25, pp381-382.

Emden, R.K.N. (1979) Channel Information Services, Improving Safety in the Dover Strait. Pratical Navigation in the Dover Strait. Proceedings of the Seminar by the Dover Branch of the Nautical of the Nautical Institute. pp2-3.

Fujii, Y.and Shiobara, R. (1971) The Anyalsis of Traffic Accidents. Journal of Navigation. Volume 24, pp534-543.

Fujii, Y.and Tanaka, A. (1971) Traffic Capacity. Journal of Navigation. Volume 24, pp543-552.

Garcia-Frias, J. (1970) The Revision of the Rules. Journal of Navigation. Volume 23, pp71-80.

Goodwin, E.M. (1975) A Statistical Study of Ship Domains.
PhD Thesis. CNAA.

Goodwin, E.M. (1978) Marine Encounter Rates.
Journal of Navigation. Volume 31, pp357-369.

Goodwin, E.M. and Kemp, J.F. (1980) Collision Risks for Fixed Off-Shore Structures.
Journal of Navigation. Volume 33, pp351-356.

Hargreaves, E.R. (1973) Safety of Navigation in the English Channel.
Journal of Navigation. Volume 26, pp399-407.

Hargreaves, E.R. (1978) Marine Traffic - The Role of Government.
Institute of Mathematics and its Applications. Conference - Mathematical Aspects of Marine Traffic. pp1-7.
Published 1979 by Academic Press.

Hollingdale, S.H. (1961) The Mathematics of Collision Avoidance in Two Dimensions. Journal of Navigation. Volume 14, pp243-261.

Hollingdale, S.H. (1977) Can Mathematics Help the Mariner?
Institute of Mathematics and its Applications
Conference - Mathematical Aspects of Marine Traffic, pp23-34.

Holmes, J.D. (1981) A Statistical Study of Factors Affecting Navigation Decision Making. Journal of Navigation.
Volume 33, pp206-214.

Johnson, D.R. (1978) Recent Trends in Navigation Safety in the Dover Strait. Marine Traffic Services - Proceedings of the Third International Symposium, Liverpool. pp171-194.

Jones, K.D. (1971) Practical Manoeuvres to Avoid Collisions at Sea.
Journal of Navigation. Volume 24, pp60-66.

Kemp, J.F. (1972) Collision Avoidance and the Mariner.
Journal of Navigation. Volume 25, pp404-406.

Kemp, J.F. (1973) Behaviour Patterns in Encounters Between Ships.
Journal of Navigation. Volume 26, pp417-423.

Kwik, K.H. (1979) Optimium Crossing Angles.
Journal of Navigation. Volume 32, pp46-52.

Lamb, W.E.P. (1979) The Simulation of Crossing Manoeuvres at Sea.
Journal of Navigation. Volume 32, pp272-275.

Le Pla, Lieut.-Commander P. R.N. (1978) Problems of Navigation in
High Density Traffic. Journal of Navigation. Volume 31, pp310-319.

Lewison, G.R.G. The Risk of a Ship Encounter Leading to a Collision.
Journal of Navigation. Volume 31, pp384-408.

Lewison, G.R.G. The Modelling of Marine Traffic Flow and Potential
Encounters. Proceedings of Conference on Mathematical
Aspects of Marine Traffic Flow. pp129-159.

Paffett, J.A.H. (1981) Recent Developements in Marine Simulation.
Journal of Navigation. Volume 34, pp166-186.

Ratcliff, S. (1982) Secondary Radar for Airbourne Collision
Avoidance. Journal of Navigation. Volume 35, pp220-241.

Spaargaren, K. and Trefon, R. (1978) Observation Related Port
Approach Traffic Simulation. Marine Traffic Services -
Proceedings of the Third International Symposium,
Liverpool. pp108-116.

Thompson, P.A. (1970) Revised Rules for Preventing Collisions at Sea.
Journal of Navigation. Volume 23, pp81-85.

Zade, G. (1978) Cost and Benefit of Natical Simulations-
a Mariner's Point of View. Marine Traffic Services - Proceedings
of the Third International Symposium, Liverpool. pp23-38.

Appendix A

Chronology of major developments in Channel safety since 1962

June 1962	-	The Institutes of Navigation in the United Kingdom, France and the Federal Republic of Germany issue a report on the regulation of traffic in converging zones, with particular reference to the Dover Straits, and make proposals for traffic routing in that area.
June 1967	-	IMCO-adopted Traffic Separation Scheme in the Dover Straits comes into effect, the first of its kind in the world.
1970/71	-	Tragic series of accidents in the Dover Straits area.
February 1971	-	Channel shipping studies begin at the National Physical Laboratory (continuing at NMI).
October 1971	-	Experimental radar surveillance begins at St Margaret's Bay near Dover.
February 1972	-	Experimental radar station is set up at Cap Gris Nez.

April 1972	-	Extended and modified Dover Straits Traffic Separation Scheme comes into effect.
May 1972	-	British Government makes the Collision Regulations (Traffic Separation Schemes) Order 1972 (effective 1 September).
July 1972	-	Experimental Dover Straits Information and Surveillance Service comes into being at St Margaret's Bay near Dover with broadcasts in English.
October 1972	-	An International Convention draws up revised International Regulations for Preventing Collisions at Sea, Rule 10 of which requires all Convention vessels to adhere to the provisions regulating IMCO-adopted Traffic Separation Schemes.
July 1973	-	AFSONG is set up by the Governments of the United Kingdom and France.
August 1973	-	The CROSSMA station at Cap Gris Nez institutes a surveillance and information service for the Dover Straits with broadcasts in French and English.
February 1974	-	Publication of the first AFSONG report.

September 1975	-	The SINM begin operations from their new centre at Cap Gris Nez (CINM).
November 1975	-	Collision between VLCC Olympic Alliance and HMS Achilles in Dover Straits resulting in a serious oil spill to which both countries respond.
February 1976	-	AFSONG's terms of reference are expanded to cover the whole of the English Channel and anti-disaster contingency planning.
August 1976	-	New radars come into operation at St Margaret's Bay and Dungeness, considering extending the Dover Strait Operations Centre's radar cover of the Dover Straits area.
June 1977	-	MANCHEPLAN is exercised.
June 1977	-	Full Scale Channel Survey is conducted.
15 July 1977	-	The International Regulations for Preventing Collisions at Sea, 1972 come into force.

July-December 1977 - The United Kingdom and France authorities intensify efforts to identify vessels contravening Rule 10 of the new Regulations. Foreign vessels are reported to their flag states for action.

Appendix B

Rule 10: 1972 Collision Regulations

Traffic Separation Schemes

(a) This rule applies to traffic separation schemes adopted by the Organization:

(b) A vessel using a traffic separation scheme shall:

(i) proceed in the appropriate traffic lane in the general direction of traffic flow for that lane;

(ii) so far as practicable keep clear of a traffic separation line or separation zone;

(iii) normally join or leave a traffic lane at the termination of the lane, but when joining or leaving from the side shall do so at as small an angle to the general direction of traffic flow as practicable.

(c) A vessel so far as is practicable avoid crossing traffic lanes, but if obliged to do so shall cross as nearly as is practicable at right angles to the general direction of traffic flow.

(d) Inshore traffic zones shall not normally be used by though traffic which can safely use the appropriate traffic lane within the adjacent traffic separation scheme.

(e) A vessel, other than a crossing vessel, shall not normally enter a separation zone or cross a separation zone except:

(i) in cases of emergency to avoid immediate danger;

(ii) to engage in fishing within a separation zone.

(f) A vessel navigating in areas near the terminations of traffic separation schemes shall do so with paricular caution.

(g) A vessel shall so far as practicable avoid anchoring in a traffic separation scheme or in areas near its terminations.

(h) A vessel not using a traffic separation scheme shall avoid it by as wide a margin as is practicable.

(i) A vessel engaged in fishing shall not impede the passage of any vessel following a traffic lane.

(j) A vessel of less than 20 metres in length or a sailing vessel shall not impede the safe passage of a power-driven vessel following a traffic lane.

QUESTIONNAIRE

Appendix C

A) PLEASE GIVE DETAILS OF YOURSELF. ALL DATA WILL BE USED PURELY FOR PERSONAL RESEARCH.

NATIONALITY AGE COMPANY

PLEASE TICK ONE BOX FOR EACH QUESTION.

YEARS AT SEA	001	PRESENT CERTIFICATE	002	PRESENT RANK	003	
3 OR LESS		UNCERT		3/o H.T.		1
4 - 6		MATE H.T.		2/o H.T.		2
7 - 9		MASTER H.T.		c/o H.T.		3
10 - 12		CLASS 4		MASTER H.T.		4
13 - 15		2ND MATE F.G.		4/o F.G.		5
16 - 20		1ST MATE F.G.		3/o F.G.		6
OVER 20		MASTER F.G.		2/o F.G.		7
				c/o F.G.		8
				MASTER F.G.		9

PLEASE TICK DETAILS OF YOUR LAST SHIP

SIZE (SUMMER D.W.T.)	004	FLAG	005	LENGTH O.A.(FT)	006	TYPE	007	ACTUAL OPERATING SPEED (KNOTS)	008	RADARS	009	
BELOW 5,000		U.K.		BELOW 300		CRUDE TANKER		BELOW 10		3 CM ONLY		1
5,000-14,999		E.E.C.		300-400		CLEAN TNNKER		10-12.9		3 CM & 10 CM		2
15,000-24,999		FLAG OF CONV.		401-500		OBO/OO		13-14.9		ANTI-COLLISION		3
25,000-39,999		COMMONWEALTH		501-600		BULK		15-17.9				4
40,000-64,999		OTHER		601-700		G. CARGO		18-20.9				5
65,000-79,999				701-800		CHEMICAL/		21-23.9				6
80,000-119,999				801-900		CONTAINER		24 OR OVER				7
120,000-160,000				901-1,000		FERRY						8
OVER 160,000				OVER 1,000		OTHER						9

IN THE FOLLOWING SITUATIONS YOU ARE OFFICER ON WATCH ONBOARD YOUR LAST VESSEL, DEEP SEA, IN CLEAR WEATHER.

A) YOU ARE BOUND TO QUEBEC FROM LE HAVRE (COURSE 270°). A SHIP IS SIGHTED 4 POINTS ON YOUR STARBOARD BOW, APPROXIMATE COURSE 180°, BEARING STEADY.

HOW CLOSE WOULD YOU APPROACH BEFORE ALTERING COURSE (N. MILES)	cc10	WHAT WOULD BE YOUR ALTERATION OF COURSE	cc11	WHAT WOULD BE YOUR MINIMUM ACCEPTABLE NEW C.P.A.	cc12	
LESS THAN 1.5 N.M.	☐	15° OR LESS	☐	6 CABLES OR LESS	☐	1
1.5 - 2.5 N.M.	☐	16° - 25°	☐	6.1 to 9 CABLES	☐	2
2.6 - 3.5 N.M.	☐	26° - 35°	☐	9.1 TO 12 CABLES	☐	3
3.6 - 4.5 N.M.	☐	36° - 45°	☐	1.21 TO 1.5 N.M.	☐	4
4.6 - 5.5 N.M.	☐	46° - 55°	☐	1.51 TO 1.8 N.M.	☐	5
5.6 - 6.5 N.M.	☐	56° - 65°	☐	1.81 TO 2.1 N.M.	☐	6
6.6 N.M. OR OVER	☐	OVER 65°	☐	2.11 TO 2.4 N.M.	☐	7
				2.41 TO 2.7 N.M.	☐	8
				OVER 2.7 N.M.	☐	9

B) YOUR COURSE IS 270°, YOU SIGHT AN OLD TANKER 4 POINTS TO PORT, APPROXIMATE COURSE DUE NORTH BEARING STEADY.

HOW CLOSE WOULD YOU LET HER APPROACH BEFORE YOU ALTER COURSE	cc13	WHAT WOULD BE YOUR ALTERATION OF COURSE	cc14	IN WHICH DIRECTION	cc15	WHAT WOULD BE YOUR MINIMUM ACCEPTABLE NEW C.P.A.	cc16	
LESS THAN 1.5 N.M.	☐	15° OR LESS	☐	ALWAYS PORT	☐	6 CABLES OR LESS	☐	1
1.5 - 2.5 N.M.	☐	16° - 25°	☐	ALWAYS STARBOARD	☐	6.1 TO 9 CABLES	☐	2
2.6 - 3.5 N.M.	☐	26° - 35°	☐	PREFERABLY PORT	☐	9.1 TO 12 CABLES	☐	3
3.6 - 4.5 N.M.	☐	36° - 45°	☐	PREFERABLY STARBOARD	☐	1.21 N.M. TO 1.5 N.M.	☐	4
4.6 - 5.5 N.M.	☐	46° - 55°	☐	EQUAL WEIGHTING	☐	1.51 N.M. TO 1.8 N.M.	☐	5
5.6 - 6.5 N.M.	☐	56° - 65°	☐			1.81 N.M. TO 2.1 N.M.	☐	6
6.6 N.M. OR OVER	☐	OVER 65°	☐			2.11 N.M. TO 2.4 N.M.	☐	7
						2.41 N.M. to 2.7 N.M.	☐	8
						OVER 2.7 N.M.	☐	9

c) YOU ARE OVERTAKING A VESSEL DIRECTLY AHEAD OF YOU, CLOSING AT 2 - 3 KNOTS.

HOW CLOSE WOULD YOU APPROACH BEFORE YOU ALTERED TO PASS.

cc17

- LESS THAN 0.5 N.M. [ ]
- 0.5 TO 1.00 N.M. [ ]
- 1.01 TO 1.50 N.M. [ ]
- 1.51 TO 2.00 N.M. [ ]
- 2.01 TO 2.50 N.M. [ ]
- 2.51 TO 3.0 N.M. [ ]
- 3.01 TO 3.50 N.M. [ ]
- 3.51 TO 4.00 N.M. [ ]
- OVER 4.0 N.M. [ ]

WHICH DIRECTION WOULD YOU ALTER.

cc18

- ALWAYS TO PORT [ ]
- ALWAYS TO STARBOARD [ ]
- PREFERABLY TO PORT [ ]
- PREFERABLY TO STARBOARD [ ]
- EQUAL WEIGHTING [ ]

WHAT WOULD BE YOUR MINIMUM ACCEPTABLE NEW C.P.A.

cc19

- 6 CABLES OR LESS [ ] 1
- 6.1 TO 9 CABLES [ ] 2
- 9.1 TO 12 CABLES [ ] 3
- 1.21 TO 1.5 N.M. [ ] 4
- 1.51 TO 1.8 N.M. [ ] 5
- 1.81 TO 2.1 N.M. [ ] 6
- 2.11 TO 2.4 N.M. [ ] 7
- 2.41 TO 2.7 N.M. [ ] 8
- OVER 2.7 N.M. [ ] 9

WHAT WOULD BE YOUR MINIMUM ACCEPTABLE C.P.A. TO A FIXED OIL PLATFORM MARKED ON THE CHART.

cc20

- 3 CABLES OR LESS [ ]
- 3.1 TO 6.0 CABLES [ ]
- 6.1 TO 9.0 CABLES [ ]
- 9.1 TO 12.0 CABLES [ ]
- 1.21 TO 1.50 N.M. [ ]
- 1.51 TO 1.80 N.M. [ ]
- 1.81 TO 2.10 N.M. [ ]
- 2.11 TO 2.40 N.M. [ ]
- OVER 2.4 N.M. [ ]

THERE ARE TUGS ATTENDING AN UNCHARTED DRILLING RIG WHAT WOULD BE YOUR MINIMUM ACCEPTABLE C.P.A.

cc21

- 3 CABLES OR LESS [ ]
- 3.1 TO 6.0 CABLES [ ]
- 6.1 TO 9.0 CABLES [ ]
- 9.1 TO 12.0 CABLES [ ]
- 1.21 TO 1.50 N.M. [ ]
- 1.51 TO 1.80 N.M. [ ]
- 1.81 TO 2.10 N.M. [ ]
- 2.11 TO 2.40 N.M. [ ]
- OVER 2.4 N.M. [ ]

WHAT WOULD YOUR MINIMUM ACCEPTABLE C.P.A. TO AN ISOLATED LIGHTHOUSE IN DEEP WATER.

cc22

- 3 CABLES OR LESS [ ] 1
- 3.1 TO 6.0 CABLES [ ] 2
- 6.1 TO 9.0 CABLES [ ] 3
- 9.1 TO 12.0 CABLES [ ] 4
- 1.21 TO 1.5 N.M. [ ] 5
- 1.51 TO 1.8 N.M. [ ] 6
- 1.81 TO 2.10 N.M. [ ] 7
- 2.11 TO 2.40 N.M. [ ] 8
- OVER 2.4 N.M. [ ] 9

HOW WOULD YOUR ANSWERS TO THE PREVIOUS QUESTIONS FOR MINIMUM ACCEPTABLE C.P.A. DIFFER IF YOU WERE PRESSED TO MAKE THE TIDE

VESSEL ON STARBOARD SIDE

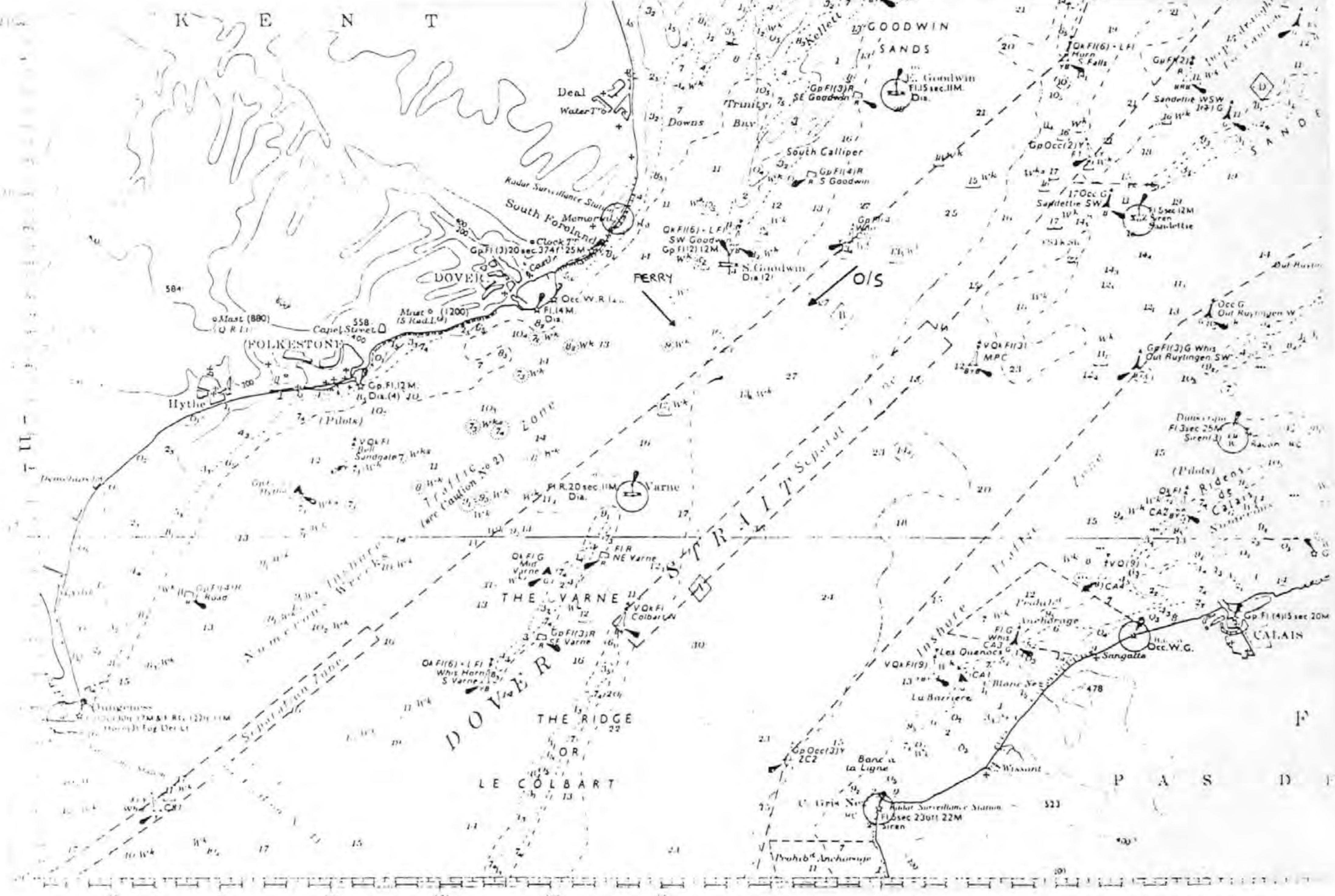
	cc32
DECREASE BY OVER 1.2 N.M.	
DECREASE BY 9.1 to 12 CABLES	
DECREASE BY 6.1 to 9.0 CABLES	
DECREASE BY 3.1 to 6.0 CABLES	
STAY ROUGHLY THE SAME	
INCREASE BY 3.0 to 6.0 CABLES	
INCREASE BY 6.1 to 9.0 CABLES	
INCREASE BY 9.1 to 12.0 CABLES	
INCREASE BY OVER 1.2 N.M.	

VESSEL ON PORT SIDE

	cc33
DECREASE BY OVER 1.2 N.M.	
DECREASE BY 9.1 to 12 CABLES	
DECREASE BY 6.1 to 9.0 CABLES	
DECREASE BY 3.0 to 6.0 CABLES	
STAY ROUGHLY THE SAME	
INCREASE BY 3.0 to 6.0 CABLES	
INCREASE BY 6.1 to 9.0 CABLES	
INCREASE BY 9.1 to 12.0 CABLES	
INCREASE BY OVER 1.2 N.M.	

CHARTED FIXED OIL PLATFORM

	cc34
DECREASE BY OVER 1.2 N.M	
DECREASE BY 9.1 to 12 CABLES	
DECREASE BY 6.1 to 9.0 CABLES	
DECREASE BY 3.0 to 6.0 CABLES	
STAY ROUGHLY THE SAME	
INCREASE BY 3.0 to 6.0 CABLES	
INCREASE BY 6.1 to 9.0 CABLES	
INCREASE BY 9.1 to 12.0 CABLES	
INCREASE BY OVER 1.2 N.M.	



KENT
GOODWIN SANDS
Deal
Downs
Trinity Bay
South Calliper
Gp Fl (4) R S Goodwin
SE Goodwin
E. Goodwin Fl 15 sec 11M Dia.
SW Goodwin
S. Goodwin
South Foreland
Radar Surveillance Station
Memorial
Clock Tr
DOVER
FERRY
O/S
Mast (880)
Mast (1200)
Capel Street
FOLKESTONE
Hythe
(Pilots)
Sandgate
Traffic Zone (see Caution No 2)
Varne
Fl R 20 sec 11M Dia.
THE VARNE
Mid Varne
NE Varne
SE Varne
S Varne
Inshore Traffic Zone
Separation Zone
Separation Lane
STRAIT
DOVER
THE RIDGE
OR
LE COLBART
Dungeness
Sandettie SW
Sandettie WSW
Out Ruytingen W
Out Ruytingen SW
MPC
Dunkerque
(Pilots)
Ridens de Calais
CALAIS
Sangatte
Occ.W.G.
Les Quenocs
La Barriere
Blanc Nez
Wissant
Banc a la Ligne
C. Gris Nez
Radar Surveillance Station
Prohibd Anchorage
PAS DE

YOUR VESSEL IS STEAMING DOWN THE WEST BOUND ROUTEING SCHEME AT FULL AHEAD STAND-BY IN GOOD VISIBILITY. YOU ARE JUST ABOUT TO PASS THE VARNE LIGHT VESSEL AND ARE APPROXIMATELY ½ N.M. INTO THE ROUTEING SCHEME. A FERRY IS ABOUT TO ENTER THE SCHEME, AIMING TO CROSS AT A RIGHT ANGLE, T.C.P.A. OF 15 MINUTES AND <u>BEARING STEADY</u> - INDICATE YOUR COURSE OF ACTION OR ACTIONS FROM THE TWO OPTIONS A & B.

A: ALTER COURSE TO STARBOARD BY:

	cc37
15° OR LESS	☐
16° - 25°	☐
26° - 35°	☐
36° - 45°	☐
46° - 55°	☐
56° - 65°	☐
OVER 65°	☐

B: ALTER TELEGRAPH TO:

	cc38	
FULL AHEAD	☐	1
HALF AHEAD	☐	2
SLOW AHEAD	☐	3
DEAD AHEAD	☐	4
STOP	☐	5
DEAD ASTERN	☐	6
SLOW ASTERN	☐	7
HALF ASTERN	☐	8
FULL ASTERN	☐	9

WHAT WOULD BE YOUR MINIMUM NEW ACCEPTABLE C.P.A.:

	cc39
6 CABLES OR LESS	☐
6.1 TO 9 CABLES	☐
9.1 TO 12 CABLES	☐
1.2 TO 1.5 N.M.	☐
1.6 TO 1.8 N.M.	☐
1.9 TO 2.1 N.M.	☐
2.2 TO 2.4 N.M.	☐
2.5 TO 2.7 N.M.	☐
GREATER THAN 2.7 N.M.	☐

GIVEN THAT YOU MADE AN ALTERATION OF COURSE, GIVE A ROUGH APPROXIMATION OF HOW FAR YOU WOULD HAVE MANŒUVRED INTO THE ENGLISH INSHORE ZONE:

	cc40	
0 - 0.5 N.M.	☐	1
0.6 - 1.0 N.M.	☐	2
1.1 - 1.5 N.M.	☐	3
1.6 - 2.0 N.M.	☐	4
2.1 - 2.5 N.M.	☐	5
2.6 - 3.0 N.M.	☐	6
3.1 - 3.5 N.M.	☐	7
MORE THAN 3.5 N.M.	☐	8
		9

YOUR VESSEL HAS NOW MADE SOME MANŒUVRE AND IF IT IS AN ALTERATION OF COURSE TO SOME DISTANCE INSIDE THE EIZ, AS APPROXIMATED EARLIER,

cc41

DO YOU FEEL IT NECESSARY TO RETURN TO THE SHIPPING LANE: YES ☐ 1
NO ☐ 2

IF YOUR ANSWER IS YES, ANSWER ANY OF THE FOLLOWING QUESTIONS THAT YOU FEEL TO BE RELEVANT:

WHAT ANGLE OF HELM WOULD YOU SET TO BRING THE SHIP AROUND ON A HEADING FOR THE ROUTEING SCHEME:

cc42

6° OR LESS ☐
7° TO 15° ☐
16° TO 25° ☐
26° TO 35° ☐
36° TO 45° ☐
MORE THAN 45° ☐

WHAT HEADING WOULD YOU SET TO RETURN TO THE ROUTEING SCHEME (ROUTEING SCHEME RUNS AT 230°T):

cc43

230° - 235° ☐ 1
236° - 240° ☐ 2
241° - 245° ☐ 3
246° - 250° ☐ 4
251° - 255° ☐ 5
256° - 260° ☐ 6
265° OR MORE ☐ 7

AT WHAT ANGLE COULD YOU ATTEMPT TO REENTER THE SCHEME:

cc44

3° OR LESS ☐
4° - 6° ☐
7° - 10° ☐
11° - 15° ☐
16° - 20° ☐
21° - 25° ☐
MORE THAN 25° ☐
SHALLOWEST ANGLE POSSIBLE ☐

WOULD YOU SET YOUR COURSE TO RETURN TO THE ROUTEING SCHEME WITH THE HOPE OF RETURNING IN A CERTAIN DISTANCE, IF SO HOW FAR:

cc45

0 TO 1 N.M. ☐ 1
1 TO 3 N.M. ☐ 2
3 TO 5 N.M. ☐ 3
5 TO 7 N.M. ☐ 4
7 TO 10 N.M. ☐ 5
GREATER THAN 10 N.M. ☐ 6
7
8

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Manoeuvring Times, Domains and Arenas

B. A. Colley, R. G. Curtis and C. T. Stockel

1. INTRODUCTION. Two main concepts in mathematical modelling of ship encounters have been proposed by Davis.[1] The first, the 'domain', was an adaptation of a concept originally introduced by Goodwin,[2] who defined the domain as the 'area about own-ship that a navigator wished to keep free with respect to ships and other stationary objects'. The second, the 'arena', conceived by Davis, is the area around the domain which when infringed causes the mariner to consider whether to make a collision-avoidance manoeuvre. Thus, in a computer model, when a vessel enters the arena the computer analyses the situation and, depending on the severity of the threat, makes a collision-avoidance manoeuvre.

Goodwin's domain was divided into three sectors corresponding to the 'give-way', the 'stand-on' and the 'overtaking' regions as defined by the relative velocity of approach. The domain was derived from radar films of ship tracks and records of radar simulator experiments. Davis smoothed the sectored domain to a circle with own-ship off-centred astern and to port, and the weighting of each of the sectors retained. Davis's domain had a solid theoretical grounding; the arena, however, was simply a larger version of the smoothed domain. Its size and position were obtained by means of a well-distributed questionnaire. It served its purpose in the model, but lacked any real validation.

2. SPEED CHANGES. One problem with the Davis arena was its inability automatically to take into account different velocities, both of own-ship and of targets. Neither could it make allowances for continuously varying relative velocity. Finally it would not compensate for any loss of speed during a manoeuvre, which was a function to be built into the model at a later date. Holmes[3] has shown the importance of speed, both relative and absolute, to modelling of ship encounters. He constructed a mathematical model consisting of the independent variables *own-ship speed* and *target speed*, which predicted the dependent variable *indirect distance* (the distance from own-ship to target via the intersection of the courses). This gives some idea of the importance to be attached to speed changes in the model. In Davis's model different values of own-ship speed could be accounted for by using a speed-dependent scaling factor; this, however, became increasingly difficult, with changing values of target speed and relative velocity and it was decided to explore new concepts.

3. RANGE/RANGE RATE. Air traffic control theory[4] proved a useful source. The theory was to test the ratio of the range and range-rate (the closing relative velocity) against a time criterion. A manoeuvre was considered and if necessary executed when the time available became less than the time required for safe manoeuvre:

$$T_r > R/\dot{R} \tag{1}$$

where T_r is the time required (min.), R is the range to target (n.m.) $\dot{R}$ is the range rate (n.m./min.). This new concept uses the relative velocity of the vessels involved in the encounter and consequently compensates for any speed changes. Since the range/range-rate theory was first used in air traffic control it had to be capable of accounting for large speed changes, both relative and absolute, making it more than adequate for a ship-encounter model.

4. STAND-ON AND GIVE-WAY. It was decided to use a time criterion $T_r = 10$ minutes for give-way situations. This fits in well with the Davis arena for two vessels of 16 knots. An improvement of this time criterion will be attempted by means of a questionnaire. The next stage was to distinguish between give-way and stand-on situations. Rule 13(*b*) of the Collision Regulations indicates that if a vessel is coming up with own-ship from a direction more than 22·5 degrees abaft the beam that vessel is overtaking, and own-ship should stand-on (Rule 10(*b*)). In a crossing situation the vessel with the other on her own port-bow stands on (Rule 15). In a mathematical model this would be approximated by requiring own-ship to give way if the other ship approached from a direction between ahead and 22·5 degrees abaft the starboard beam, except that, if overtaking, the sector should be extended to cover the port bow. Initially it was felt that the Davis domain would serve adequately as a 'hard core arena' relating to the stand-on sector. It was, however, proposed that a model catering for speed changes in the give-way case should also do so in the stand-on case. This led to developing an equation for the safety distance for last-minute action (l.m.a.):

$$R_s = \frac{(U+V)}{60} * \frac{09}{\dot{\psi}} \tag{2}$$

where U is own-ship speed (knots) V is target-ship speed (knots) R_s is the safety distance for l.m.a. (n.m.) $\dot{\psi}$ is the rate of turn (degrees/min.). This fits in well with the present range/range-rate concept. If $(U+V)/60$ replaces $\dot{R}$ and $90/\dot{\psi}$ is regarded as the time required, then we have a new model for the stand-on case. The model can be further improved by modifying the time required to take account[5] of the ship's response time while setting the mariners' reaction time to zero as the target would already have been tracked visually at this stage. Thus in stand-on situations:

$$T_r = \frac{(90+A)}{\dot{\psi}} + T_d \tag{3}$$

where T_r is the time required, A is the derivation angle, T_d is the physical time delay before the vessel responds to the helm.

5. INITIAL PROBLEMS. The first problem with this model arose as the relative velocity tended towards zero when the two vessels were on nearly parallel courses, own-ship being overtaken. If the two ship speeds were nearly the same, therefore, the range at which the manoeuvre was considered, and if necessary executed, became very small. The polar diagrams, which assume a

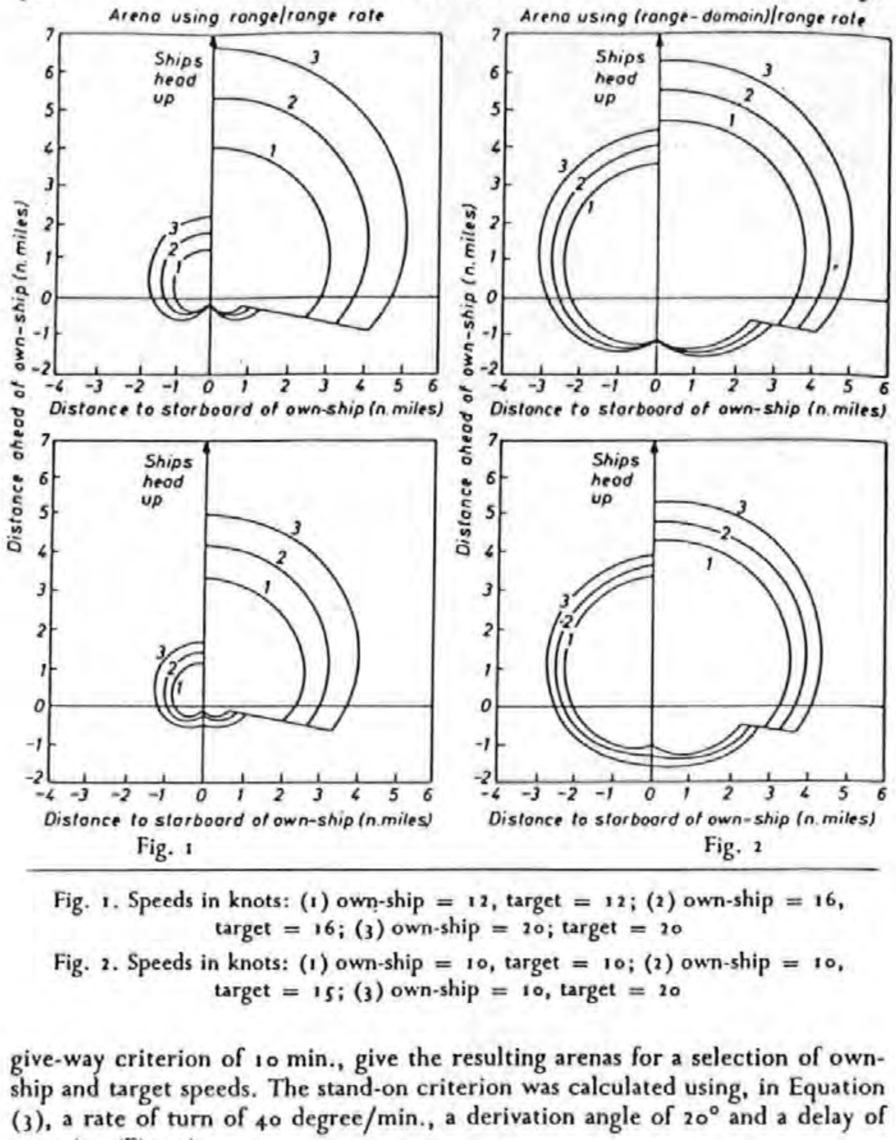

Fig. 1

Fig. 2

Fig. 1. Speeds in knots: (1) own-ship = 12, target = 12; (2) own-ship = 16, target = 16; (3) own-ship = 20; target = 20

Fig. 2. Speeds in knots: (1) own-ship = 10, target = 10; (2) own-ship = 10, target = 15; (3) own-ship = 10, target = 20

give-way criterion of 10 min., give the resulting arenas for a selection of own-ship and target speeds. The stand-on criterion was calculated using, in Equation (3), a rate of turn of 40 degree/min., a derivation angle of 20° and a delay of 0·5 min. (Fig. 1).

The problem occurred when the two vessels were of similar speeds in an overtaking situation. Since we were not at the time considering own-ship overtaking, the problem mainly affected the stand-on criterion. It did, however, have a significant effect on the give-way model.

6. SOLUTION. Rather than assessing the time available as the time taken for the target to reach own-ship, the mariner tends to gauge it as the time taken to reach an area around own-ship which he wants to keep clear of other ships, that is the domain. Thus the new model replaced range/range-rate by range to domain/range rate (RDRR); mathematically this was achieved by replacing Equation (1) by

$$T_r > (R - R_d)/\dot{R} \tag{4}$$

where R_d is the domain.

In the worst possible case of two vessels with identical speeds slowly converging, the minimum manoeuvring distance will be equal to the domain. The same principle was adopted for the give-way model but, since the original time criterion of 10 min. was obtained to best fit Davis's arena, it must be scaled down to cater for the addition of the domain. Thus a new give-way criterion of 6 min. was used.

The new mathematical model was similar to the ATC automatic warning standard, but our domain varies with relative bearing. In the ATC model there were a series of risk levels which could be employed. Each risk level used the range to a particular constant distance from own-aircraft (a circular domain around the aircraft). For each level it also had a unique time criterion. In the RDRR model the range was also taken to the edge of the domain, the difference being that our domain varies with relative bearing. The result is a risk level that varies as a function of the relative bearing. Thus, assuming the values for the domain and parameters defining the stand-on criterion remains as previously defined, and setting a new value of $\delta T_r = 6$ min. for the give-way criterion, the new arena shown in Fig. 2 was calculated. This significantly improves the model, with a minimum approach 1·03 n.m., occurring when own-ship was being slowly overtaken from astern.

The last refinement considered was a variation of the manoeuvring range with closest point of approach (CPA). It was concluded however, that since when using a domain to determine the threat of the target, the target was either regarded as a threat or completely safe, allowance for CPA and inclusion of the domain could not usefully go together. Thus, since the arena uses the domain in its construction it has no intermediate degree of safety or threat, and to incorporate an idea using CPA would go against the present principles.

7. CONCLUSION. The main advantages of the range-to-domain/range-rate concept are that the model automatically makes allowances for: (1) differing own-ship and target speeds; (2) changing relative velocity; (3) changes in own-ship speed through an alteration of course.

Other subtle improvements were possible. First, a development of the model could be a stochastic variation of mariners' reaction times to the arena. It would be a simpler task to integrate this into the RDRR model than to the Davis model. Secondly, when own-ship is overtaking, the Davis arena would demand that own-ship manoeuvres at the same range as if the vessels were on reciprocal courses. Davis investigated whether own-ship was in an overtaking situation, and it if was he would adopt a different model. With the new model, however, this was taken care of by the RDRR criteria. Even in the case where the two vessels were closing slowly and own-ship was overtaking, the minimum distance that own-ship would manoeuvre would be at the domain.

REFERENCES

[1] Davis, P. V., Dove, M. J. and Stockel, C. T. (1980). A computer simulation of marine traffic using domains and arenas. This *Journal*, 33, 215.

[2] Goodwin, E. M. (1975). A statistical study of ship domains. This *Journal*, 28, 328.

[3] Holmes, J. D. (1979). *Some Aspects of Multivariate Statistical Analysis with Application to Navigation Decision Making*. (Ph.D. Thesis, City of London Polytechnic.)

[4] Ratcliffe, S. (1982). Secondary radar for airborne collision avoidance. This *Journal*, 35, 220.

[5] Zajonc, N. (1980). Safety distance for last-minute action. (Radar Simulator Teachers' Workshop, Liverpool Polytechnic).

[6] Curtis, R. G. (1977). An analysis of the dangers of ships overtaking. *Mathematical Aspects of Marine Traffic*, Academic Press.

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A Marine Traffic Flow and Collision Avoidance Computer Simulation

B. A. Colley, R. G. Curtis and C. T. Stockel

In a previous paper[8] a model was outlined for an encounter between two vessels using the 'range to domain over range rate' (RDRR) criterion. This paper shows how the model has been developed to simulate traffic flow and collision avoidance through the main south-west bound lane of the Dover Strait traffic separation scheme. B. A. Colley and C. T. Stockel are at Plymouth Polytechnic, R. G. Curtis with the Department of Trade and Industry. The paper was presented at an ordinary meeting held in London on 16 November 1983.

1. INTRODUCTION. The rapidly increasing sophistication of computer-based vessel traffic surveillance and advice services in narrow and congested straits has given rise to a need for a mathematical model to simulate the effect of altering the system or imposing constraints on the traffic flow. Such a model provides information to personnel to decide on the best traffic management measures in the event of routine reorganization or disaster partially blocking the scheme. Two quite different approaches have in the past been used in the development of such a model.

The first approach uses what can be termed the 'macro-scale' model, which deals with the system as a whole. This, in very simple terms, means that inputs to and the constraints on the system are used in the construction of the model. If we define the set of actual encounters in an area of sea for a particular period of time as being the number of times that two vessels approach within a certain distance D of each other, then the set of potential encounters is made up of the set of actual encounters plus the situations in which an initial closest point of approach (CPA) was increased to a level above D by a collision avoidance manoeuvre. Barratt[1] developed a mathematical model to determine the number of potential encounters in a traffic routing scheme given the initial flow rates. Degré and Lefevre[2] used a computer simulation model to plot ship tracks through the Dover Strait and English Channel and hence predict the number of potential encounters. Both these models can only measure the number of potential encounters, since neither has the facility to allow vessels to make collision avoidance manoeuvres. Neither are they able to simulate the way in which a traffic flow pattern is affected by collision avoidance manoeuvres between ships.

The second approach models accurately the smallest building blocks and then pieces these individual units or modules together to obtain a view of the system as a whole. This approach, often used in the construction of computer programs, is known as the modular approach. It is also used a great deal in the natural sciences in forecasting and other dynamic models. It is worth noting that the modular approach has only been made possible with the advent of the computer, since navigational accuracy over current in-service arrangements. Fig. 10 illustrates errors in navigation measured during repeated routes using independent navigation aids. Fig. 11 shows the improvement in accuracy if the aids are integrated. Significant fuel savings can result.

A problem experienced in recent years in both military and civil aircraft is the inordinate time required for setting up the frequencies of radio aids and interpreting them, and the tedious and error-prone reference data insertion of the inertial systems. Future cockpits and flight decks are likely to offer automatic data and frequency insertion with the aid of magnetic tapes or digital data stores. Current methods employ push buttons.

16. CONCLUSIONS. It is some 75 years since Cody flew in his rudimentary cockpit at Farnborough. Since then we have experienced enormous advances. While man is involved in the loop, the human factor will always be present. The advanced systems of today cannot ensure that he is thoroughly aware of everything that is going on; their total operation is too complex for the mind to grasp, but it is essential that he remains sufficiently aware to ensure that the aircraft does precisely what is required and that in the event of failure he is not left with an impossible situation. The very act of automating systems reduces the aircrew 'hands on' experience. The high cost of flying means that training is costly, so that much of it is performed in simulators.

The modern airframe lasts for decades and performance in terms of speed alters little. It is likely that such airframes will require one or two radical phases of modification by engine and avionics replacement as the explosive growth in electronic and other technology continues. Thus the cockpits and flight decks must be designed with an eye to future modification. Without man in the loop, they need not exist, but despite reduction in crew numbers over recent years there is no sign that pilots will be superfluous, at least in the foreseeable future.

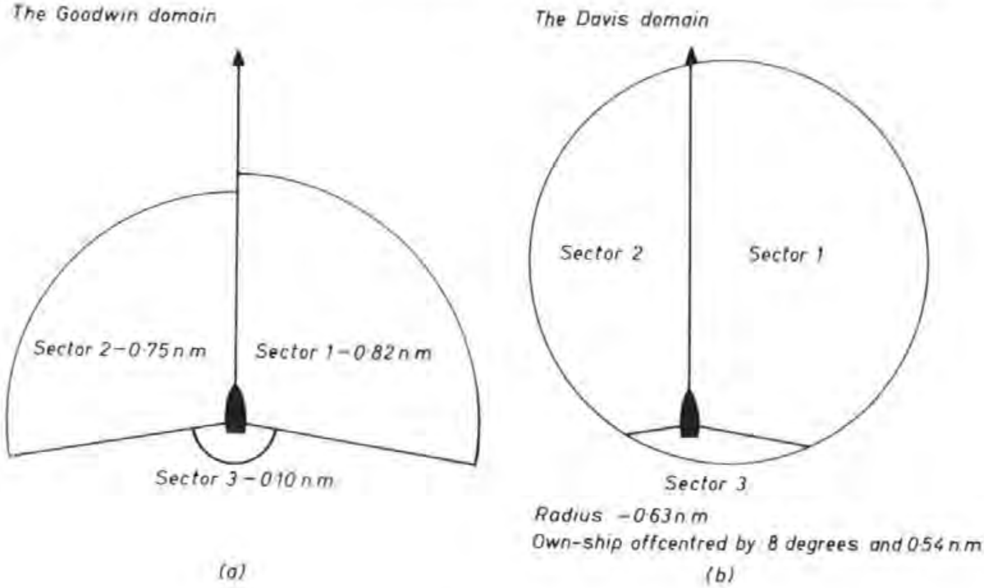

The Goodwin domain
Sector 2 – 0·75 n.m
Sector 1 – 0·82 n.m
Sector 3 – 0·10 n.m
(a)
The Davis domain
Sector 2
Sector 1
Sector 3
Radius – 0·63 n.m
Own-ship offcentred by 8 degrees and 0·54 n.m
(b)

Fig. 1

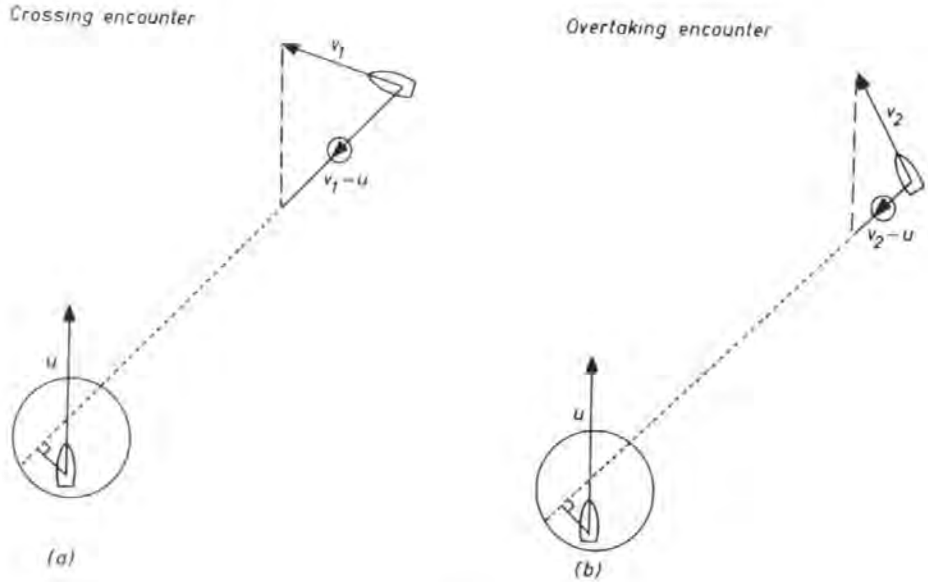

Crossing encounter
v_1
$v_1 - u$
u
(a)
Overtaking encounter
v_2
$v_2 - u$
u
(b)

Fig. 2

it allows the repetition of a particular computational strategy a great number of times.

Curtis[3] and Goodwin[4] have both made detailed studies of mariners' behaviour in collision avoidance manoeuvres. Curtis used data obtained from experiments run on the City of London Polytechnic radar simulator to obtain mariners' reaction times. From these he derived a means of calculating a minimum safe overtaking track separation for the two vessels involved in the encounter.[5,6] Goodwin's work on mariner behaviour resulted in a concept known as the domain.[4] Davis *et al.*[7] used the Goodwin domain in their computer simulation of marine traffic. Colley *et al.*[8] then refined the Davis model by the introduction of the 'range to domain over range rate' (RDRR) concept. This and the use of several circular domains is discussed later in this paper.

The concepts of the domain and the RDRR were then used in the formulation of the ship encounter model, which together with the International Regulations for Preventing Collisions at Sea is used in the simulation of an actual area of sea. In this way it can be demonstrated how 24 hours of continuous traffic through the main westbound lane of the Dover Strait traffic separation scheme can be accurately modelled.

2. DOMAIN THEORY. The domain is defined by Goodwin[4] as 'the effective area around a ship which a navigator would like to keep free with respect to other ships and stationary objects'. Goodwin obtained her domain for a specific sea area by measuring the actual density of shipping around a series of 'centre-ships'. The domain was subdivided into three sectors by the relative bearing of the target. If zero degrees is taken as ship's head, then the three sectors were defined as: $0° < \theta < 112{\cdot}5°$, starboard sector (sector 1); $112{\cdot}5° < \theta < 247{\cdot}5°$, stern sector (sector 3); $247{\cdot}5° < \theta < 360°$, port sector (sector 2).

Thus for different areas of sea a value of the domain radius for each sector was found (Fig. 1a). For the Dover Strait, values (in nautical miles) obtained were: sector 1 0·82, sector 2 0·77, sector 3 0·10. Davis *et al.*[9] initially used Goodwin's domain in their ship encounter model, but decided that the discontinuities at the sector boundaries would cause problems in the simulation and as a result the sectored domain evolved into the off-centred circle domain (Fig. 1b). This had the advantage of being a smooth, easily modelled concept, which retained the weighting of the Goodwin domain sectors. This domain was considered to be the most effective single domain for use in a computer simulation of shipping.

Encounter Types. A major problem with the Davis domain is its inability to distinguish between two different encounters with targets on the same relative bearing. It can be seen, in Fig. 2a, that own ship and the target are involved in a crossing encounter, whilst in Fig. 2b own ship is overtaking the target. The test for domain infringement is if the closest point of approach (CPA) is less than the domange (the domange is the distance from own ship to where the target's relative track cuts the domain), therefore since both targets have the same relative tracks the CPA is being tested against the same domange. Thus both encounters may be said to be regarded by the give-way vessel with the same degree of threat. It is clear that no single domain has the capacity to recognize the difference between the two encounters shown in Fig. 2a and Fig. 2b or indeed

TABLE 1

Crossing encounters

CPA	0·0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	Total
No. manoeuvring	0	0	1	4	16	20	24	26	101
No. not manoeuvring	5	12	26	28	26	20	12	4	133
Total no. observed	5	12	27	32	42	40	36	30	234
Percentage not manoeuvring	0	0	4	12	38	50	67	87	—

This gives a crossing domain of 0·50 n.m.

Head-on encounters

CPA	0·0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	Total
No. manoeuvring	1	0	4	4	1	0	0	0	10
No. not manoeuvring	0	0	2	11	14	11	5	2	45
Total no. observed	1	0	6	15	15	11	5	2	55
Percentage not manoeuvring	0	0	33	73	93	100	100	100	—

This gives a head-on domain of 0·24 n.m.

Stand-on and overtaken manoeuvres

CPA	0·0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	Total
No. manoeuvring	0	3	0	1	0	0	0	0	4
No. not manoeuvring	0	1	11	23	30	22	15	16	118
Total no. observed	0	4	11	24	30	22	15	16	122
Percentage not manoeuvring	0	25	100	96	100	100	100	100	—

Domain size unattainable

Overtaking manoeuvres

CPA	0·0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	Total
No. manoeuvring	2	4	12	6	2	0	0	0	26
No. not manoeuvring	0	1	6	7	6	4	4	0	28
Total no. observed	2	5	18	13	8	4	4	0	54
Percentage not manoeuvring	0	20	33	54	75	100	100	100	—

This gives an overtaking domain of 0·29 n.m.

a particular CPA (sign of the contribution initially ignored) was calculated. The calculated proportion is an estimate for the probability of domange being less than or equal to the specified value. This was repeated for each type of encounter. The initial results of these observations are summarized in Table 1. They refer to observations of manoeuvres in the Dover Strait.

3. ARENA THEORY. As mentioned previously, Davis[7] used a larger version of the domain as his arena. It was suggested that, rather than determine the point

between a head-on and an overtaking encounter. The solution was in the use of a different domain for each type of encounter.

Stages in manoeuvre. An encounter-manoeuvre can be split into the following stages: (a) determination of the status of own ship; (b) calculation of whether the target is a threat; (c) the time at which to manoeuvre; (d) the magnitude of the manoeuvre; (e) the time at which to alter back on to course.

Of these five stages the first does not involve the domain concept. The evaluation of a threat is determined by domain infringement. Colley *et al.*[8] showed that the time at which to manoeuvre can be determined as a fixed length of time before the target is due to infringe the domain of own ship. Similarly, the magnitude of the avoiding manoeuvre can be determined by the rudder being held over until the domain will no longer be infringed.

The decision of when to alter back is not necessarily determined by the domain. It is more likely to be a function of the relative bearing of the target. Hollingdale[10] quoted Kemp's suggestion that a ship manoeuvres back on to course when the target bearing has moved further abeam than own ship's initial course. There may, however, still be a necessity to test against domain infringement, since it is possible for the target vessel to make some sudden unexpected manoeuvre.

The original method, used by Goodwin,[4] in determining the radius for each sector of the domain, resulted in all the stages from the initial encounter recognition process to the conclusion of the manoeuvre being incorporated in her domain. It is possible that all stages make use of the same domain throughout the encounter, but the domain used in the encounter model is to determine whether a vessel is threatening. Thus although Goodwin's domain is a true measure of the shipping system as a whole it was developed using data superfluous to the requirements of the threat domain.

Domain representation. It was felt that the use of a single domain in an encounter-manoeuvre simulation was insufficient and that there was a requirement for a domain for each type of encounter. It was decided that, because of the extra degree of complexity introduced as a result of using multi-domains, circular domains should be used. Thus a mariner can be said to wish to keep the miss distance greater than a predetermined minimum distance (the domain) which is dependent on the type of encounter. The assumption is that there exist four 'threat domains', which correspond to the head-on, crossing, overtaking and stand-on encounters. These form four concentric circles about own ship.

A time-lapse cine-film of the radar screen at HM Coastguard, St Margaret's, set to the 6 n.m. off-centred range, was used for the analysis. All two-ship encounters were recorded, an encounter taken as being when two vessels had an initial CPA of less than 1 n.m.

The following variables were recorded: (a) the status of own-ship relative to the target (head-on, etc.); (b) whether a manoeuvre was executed or not; (c) (if a manoeuvre was executed) the initial predicted CPA; (d) (if a manoeuvre was not executed) the actual CPA. The CPA was considered positive if it resulted in the sight-line from own ship to target rotating in an anti-clockwise direction (positive contribution).

Thus for each encounter type the proportion of vessels not manoeuvring at at which avoiding action is taken as being at a certain distance from own ship (arena concept), the action should be a function of the time taken to the CPA of own ship. Thus when the time taken (range/range rate) becomes equal to some critical time, the manoeuvre is executed. The idea was developed by Colley *et al.*[8] to be the time taken for the target to reach the domain boundary (RDRR concept). The RDRR concept has the following advantages over the arena developed by Davis.

(a) Since the concept uses the range rate or relative velocity in its calculation, it has the ability automatically to take different ship speeds into account. Thus two very fast vessels will manoeuvre at a greater distance than two slower vessels.

(b) The concept is able to discern between vessels approaching from different bearings since relative velocity is a function of the bearing. Two vessels meeting head-on have a larger relative velocity than two vessels involved in an overtaking encounter, and as a result the two involved in the former manoeuvre at a greater distance than the two involved in the latter encounter.

(c) The model has the ability to take into account any reduction in speed by either the target or itself (at present speed changes are not incorporated in the model).

(d) A stochastic variation in human reaction times may now be introduced as a standard deviation of the time criterion. A reaction time variation would have been far more complicated to superimpose on a distance-based arena.

4. THE SHIP ENCOUNTER MODEL. The computer simulation model is a computer program, written in Fortran 77, which, although run on a PR1 ME system, is compatible with most systems using Fortran 77. The model uses a 'continuous time' as opposed to a 'discrete time' simulation procedure. This means that the information is updated at every chosen time interval, rather than as in the case of 'discrete time', when the updating of information takes place at the next point of action. The 'discrete time' model was not used because it was felt that little would have been gained, due to the almost continuous interactions between vessels, for what would have been a more complicated and hence unpredictable program. The time interval, known as the iteration time, chosen was 20 seconds, to represent the shortest practical time period likely to be discerned in analysing mariners' manoeuvring actions.

As mentioned earlier, the arena concept is no longer used. Instead a mariner is said to manoeuvre when the RDRR becomes less than some critical value. A value of 5·5 minutes was determined from an analysis of the times to closest point of approach (TCPA) of encounters from the radar film. This time is called the RDRR infringement, which corresponds to the concept of domain infringement. Thus every 20 seconds or single time iteration the simulation analyses each ship pair, calculating the status, positions, courses, relative bearing and other relevant factors. The encounter type is determined at a period prior to RDRR infringement. It was decided that a time of 3 minutes would be the most suitable for this period, corresponding to the minimum time required for a mariner to ascertain a vessel's relative track from a radar plot. Thus the encounter type is determined 8·5 minutes before domain infringement. Once the encounter type is determined it is not allowed to alter for that ship pair, which is as indicated in the International Regulations for Preventing Collision at Sea. At the time of RDRR infringement the relative track of the target is calculated and domain infringement tested. If domain infringement occurs then the target is said to be a threat, and as long as own ship is not stand-on then a manoeuvre is initiated that depends on own ship's status.

Crossing encounters. If at RDRR infringement own ship is give-way to a crossing vessel then an alteration to starboard is executed every subsequent iteration (time of 20 s) until the domain is no longer infringed. The vessel is not permitted to alter past the reciprocal course of the target. Own ship then continues on the course that just avoids domain infringement. It then starts to resume course when such an alteration will no longer result in domain infringement. On resuming its original course domain infringement is still checked at every time iteration.

Overtaking. An overtaking vessel obeys the same rules in avoiding the domain, and its encounter type determination is the same as the give-way vessel in a crossing encounter. It has however, the option of altering course to pass astern, or paralleling the target's course and passing ahead. These choices are independent of which quarter the target is on, but are a function of whether the overtaking vessel is initially passing ahead or astern. Own ship then alters back on to course as in the crossing case.

Head-on. The head-on encounter follows the same set of rules as the crossing encounter unless the two vessels are meeting green to green, in which case, if the separation is greater than half the domain, own ship manoeuvres to port.

Model idealisation. One aspect in which the model differed slightly from the practical behaviour of mariners appeared in the determination of the type of encounter. At sea it was possible for one mariner to think he was being overtaken whilst the other vessel was acting as if he was stand-on. This was because an encounter could be assigned different types depending on when it was determined by different mariners. The model did not permit any such ambiguity, determining both own ship and target encounter types simultaneously and only allowing acceptable combinations. It had been argued that a simulation should be as realistic as possible and should therefore have its quota of the human frailties. The counter-argument was more potent however, stressing that a model should depict the realistic situation whilst obeying the 'rules'. Since the Collision Regulations never intended such ambiguities, they have not been incorporated in the encounter model.

Multi-ship encounter. A multi-ship encounter (encounter involving more than two ships) can be subdivided into a number of two-ship encounters. The only complication on the two-ship encounter was that if a vessel was being threatened by more than one target an algorithm, or rule of thumb, for determining the most threatening ship was required. The algorithm used was to test the TCPA. Thus the most threatening target was the vessel with the smallest TCPA.

5. THE SIMULATION OF AN AREA OF SEA. The Dover Strait, which at its narrowest point is some eighteen nautical miles wide, is an area of significant potential hazard (Fig. 3). The traffic is divided into four zones (English inshore, main south-westbound lane, main north-eastbound lane and French inshore). Cross-channel traffic navigates across these zones on reasonably well-defined routes.

The Dover Strait was chosen for the following reasons: (*a*) the significant potential hazard inherent in the area necessitates a means of measuring the efficiency of the present system; (*b*) the high possibility of partial obstruction to the traffic separation scheme such as pipe-laying operations, Navy manoeuvres or future oil-drilling activities call for a model that can consider the advantages and disadvantages of subsequent modifications; (*c*) the availability of high-quality 16 mm films of one of the radars at HM Coastguard Station at St Margaret's Bay; (*d*) the close proximity of ferry masters whose assistance provided useful hints and data, and whose ships comprise the majority of crossing vessels.

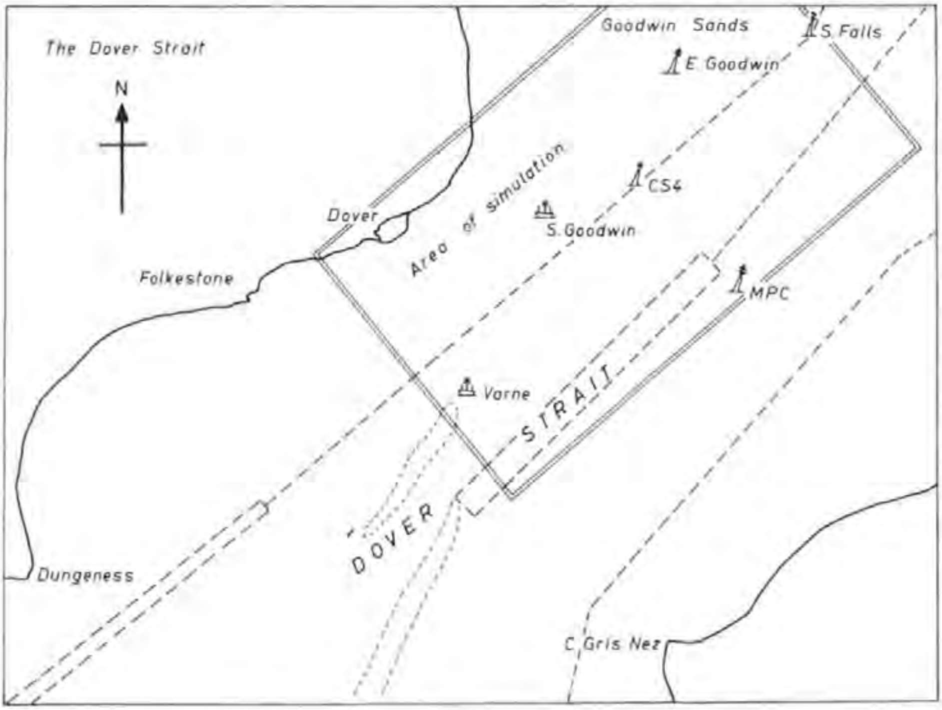


Fig. 3

A computer simulation has been produced of all shipping through a section of the main south-westbound lane, from the Varne light-vessel to the South Falls buoy (Fig. 3). It can be seen that the area of simulation highlighted in Fig. 4 has been rotated so that it runs parallel to the northern boundary of the main south-westbound lane. This facilitates any future gate counts of main lane traffic and allows for a greater concentration on the area of interest by not having to include a large amount of the main north-eastbound lane. It was decided to model simply the main south-west- as opposed to the main north-eastbound lane because of the availability of the high-resolution 6 n.m. range radar film. This film had the advantage over the 24 n.m. film of allowing an accurate analysis of encounters. The model has the capacity to deal with approximately 200 vessels over a 24-hour continuous run.

Route planning. In the ship encounter model any vessel need only be set up with an initial course and speed, since one is not interested in its absolute position but in the relative positions of vessels around it. In the simulation of a large area of sea, however, vessels not only make collision avoidance manoeuvres but they also need to make navigation course alterations. Since no two vessels follow the same track, the most frequently used tracks were determined. These were found by covering the area in a series of gates and comparing the subsequent gate sequences. These routes were then compared and the most frequently used routes selected (Fig. 4). Thus every vessel entering the simulated area is assigned one of these predetermined routes.

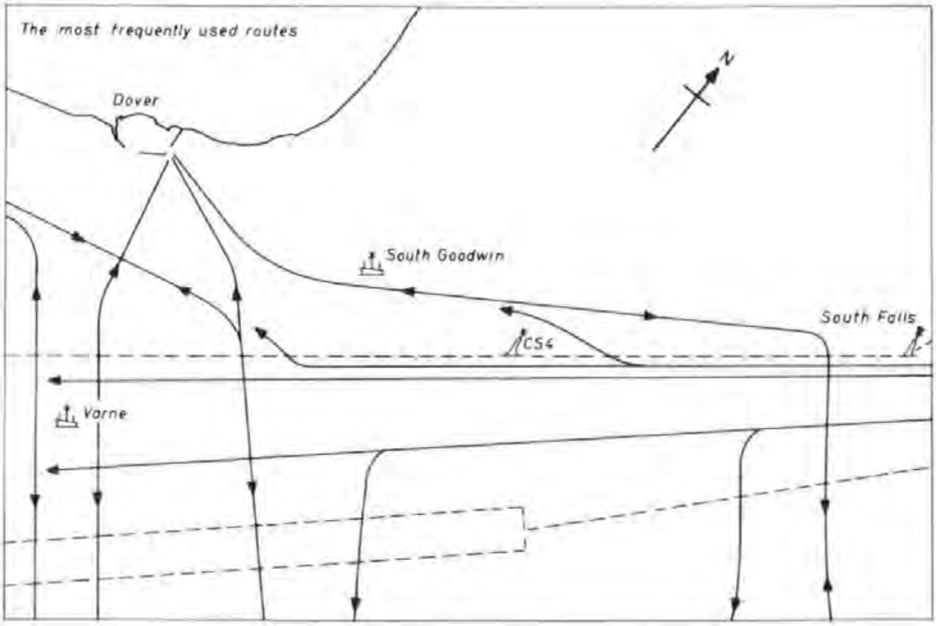


Fig. 4

It might initially appear that a suitable method of implementing the different ship routes would have been to define each ship route as a set of course alterations at set durations after the relevant vessel had entered the scheme. Indeed, this approach is used as a means of setting the tracks of target ships in the majority of radar training simulators. This method fails, however, if a vessel is forced to make a collision avoidance manoeuvre. There are two reasons for this: first, any collision avoidance manoeuvre will slow the vessel's progress and result in all subsequent navigation alterations occurring earlier in the scheme; secondly, this method has only the capability of recording the desired course on the desired route; once a vessel has been forced off the route there is no way of compensating for the resulting lateral displacement.

It was decided that the best method was to superimpose a grid on the area. Each route may now be defined by a unique set of directions on that grid. Thus,

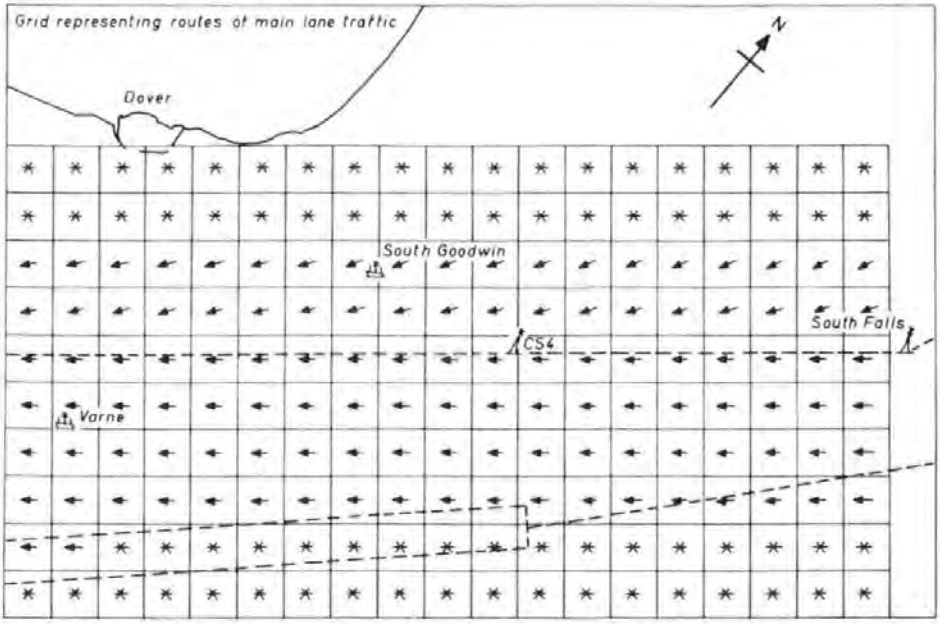

Grid representing routes of main lane traffic
N
Dover
South Goodwin
South Falls
CS4
Varne

Fig. 5a

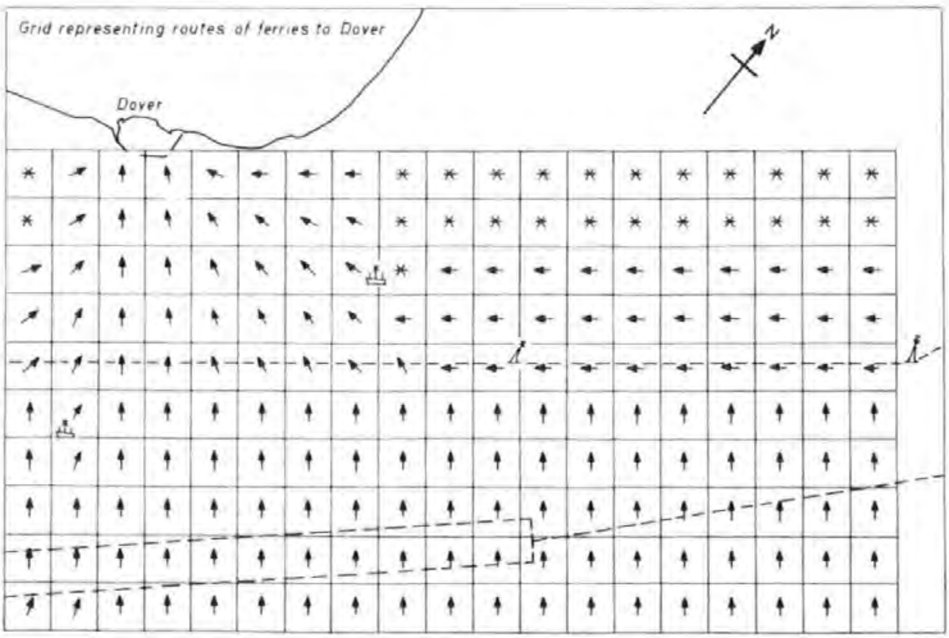

Grid representing routes of ferries to Dover
N
Dover

Fig. 5b

since any vessel's position is known at any time in the run, so the relevant grid section can be determined and the desired course relating to that ship's route made immediately available.

It was decided that the most suitable size for the grid sections would be 1 n.m. square. This was enough to describe accurately all the routes. Furthermore, it was decided that since the majority of routes did not run east–west but tended to run either parallel or perpendicular to the routing scheme, the grid's main axis should also run parallel to the separation zone boundary. So as to incorporate the whole area the origin was sited approximately 3 n.m. south of the Varne light-vessel and the grid then ran 20 n.m. by 10 n.m. so as to cover completely the area from the Varne light-vessel up to the Dover harbour mouth and as far north-east as the South Falls buoy.

Figs. 5a and 5b show examples of routes superimposed on the grid. The arrows indicate the desired course of a vessel in that section of the grid. The stars indicate a region that a vessel belonging to that route should not be in, but if so then assumes the previous desired course. Thus it can be seen that Fig. 5a describes the route taken by vessels navigating down the main lane, Fig. 5b shows how ferries navigate to Dover.

It can be seen in Fig. 5b that a ferry's route is determined solely by its destination. Thus all ferries from Boulogne, Calais and Zeebrugge to Dover make use of the same route grid or matrix. This assumption is based on the hypothesis that all ferries have roughly the same characteristics, and as a consequence their home passage is solely dependent on their present position. For example a Boulogne–Dover ferry forced to manoeuvre onto the normal Calais–Dover route would then follow the Calais ferries' route.

A problem that arose from the use of the route matrix was the tendency for vessels to parallel each other's courses, giving rise to an unnatural 'tram-line' traffic flow. This was the result of vessels of the same route type passing through the same grid sections and consequently being assigned exactly the same desired course. A simple solution was to add a random course increment of between -5 and 5 degrees on to the assigned course and then to apply the same increment over the next two or three grid sections. This meant that by the time vessels had reached the main scheme they were dispersed enough not to have to pass through the same grid sections.

Vessel types. The vessel types were determined by the characteristics that could be determined from the radar film. This led to the formulation of five distinct ship types.

The first four types include all vessels that are not cross-Channel ferries. They were categorized as follows: type 1, 15–20 kt; type 2, 10–15 kt; type 3, less than 10 kt; type 4, greater than 20 kt. It is a valid argument that a VLCC travelling at 14 kt. is unlikely to have similar characteristics to a general cargo vessel of 2000 d.w.t. travelling at the same speed. To draw any real conclusions, other than the operating speed, would have necessitated an estimation of the size of the vessel from the size of the echo. There are, however, many influences on the size of the radar return echo. These include the distance from the receiver, aspect, sea state and atmospheric conditions, etc. It was felt therefore that the best method would be simply to categorize a vessel's type by its observed speed.

The one exception to this generalization is the fifth ship type, the crossing ferry. Although their speed range puts them in either the type 1 or the type 4 range, their manoeuvrability alone puts them in a class of their own. Their type can be determined by their tracks and so the problem of having to approximate the size via the echo size does not arise. A further reason for putting the ferries in their own type class was their unique interactions with other vessels. Since a head-on encounter between ferries is a common occurrence and often aided by v.h.f. radio communication their track separation is small, whereas if vessels other than ferries meet head-on it is likely that one is a rogue and as such the encounter is far more likely to be deemed threatening.

Depth contours and land. Contours were taken from the Admiralty chart of the Dover Strait and were at depths of every 2 m down to 20 m below chart datum. Each contour is in the form of a series of positions approximately 0·25 n.m. apart. They were extracted from the chart by the use of a Calcomp Digitizer attached to the computer.

To avoid going aground, each vessel scans the whole of the depth contour relevant to its draught at every time iteration (every 20 s). It regards every point in the contour as a stationary target. If any of these 'targets' is within threatening range its CPA is determined. If any point's relative track is infringing the vessel's domain, then the vessel must take avoiding action.

The position of the coastline was entered into the computer again using the digitizer, but its purpose was totally superficial since a simulated vessel manoeuvres at the contour at which it will go aground. The use of land is simply as a visual aid in recognizing the area on plots of ship tracks. From now on a vessel's 'relevant contour' will be termed land.

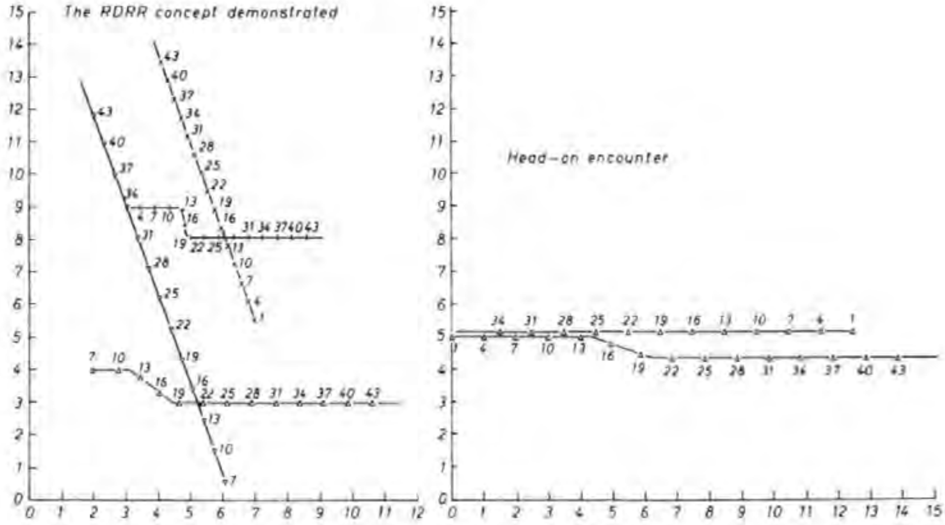
Buoys. Buoys are treated in a similar fashion to land. The only difference is one of priority. Given simultaneously buoy and land domain infringement, a vessel will treat the land with greater caution. If a vessel is being threatened by land and another vessel then if the vessel can avoid both with the same manoeuvre it will, otherwise it will give precedence to the land. However, in the same situation, with a buoy and another vessel, the vessel will always be given priority.

The Routing scheme boundaries. At first it was thought that the boundaries to the main traffic lane should be treated as 'soft land'. That is, a vessel would be reluctant to cross the boundary unless forced to do so in a collision avoidance manoeuvre. It was felt, however, that there was no such obstruction in mariners' minds as far as the inshore zone/main south-westbound lane boundary was concerned. It was deemed to be a necessary requirement at the boundary to the separation zone. It is only possible for a vessel to manoeuvre out of the south-westbound lane and into the separation zone through an overtaking manoeuvre. It was decided, therefore, that a preferential manoeuvre to starboard would always be attempted when overtaking in the vicinity of the separation zone.

The desire not to cross the northern boundary is accounted for in the course matrix, in that if a vessel does cross into the inshore zone then its new desired course will attempt to bring it back into the scheme. Further, the degree of urgency for a vessel to return to the main lane increases the further it is displaced from the boundary into the inshore zone.

6. MODEL ASSESSMENT. The following are typical examples of the simulation manoeuvres produced by the RDRR model. The axes are graduated in 1 n.m. to show the scale, and the time in minutes and a symbol are drawn every 3 minutes along the track of the ships.

Broad crossing encounter (Fig. 6). This diagram shows two broad crossing encounters which are independent of each other. The top encounter has a 9 kt vessel give way to a 12 kt vessel, whilst the bottom encounter has a 15 kt vessel give way to a 20 kt vessel. The important point to note is that both give-way vessels manoeuvre at the same time from domain infringement, which due to the different closing speeds of the two ship pairs results in a much shorter distance for the former encounter.



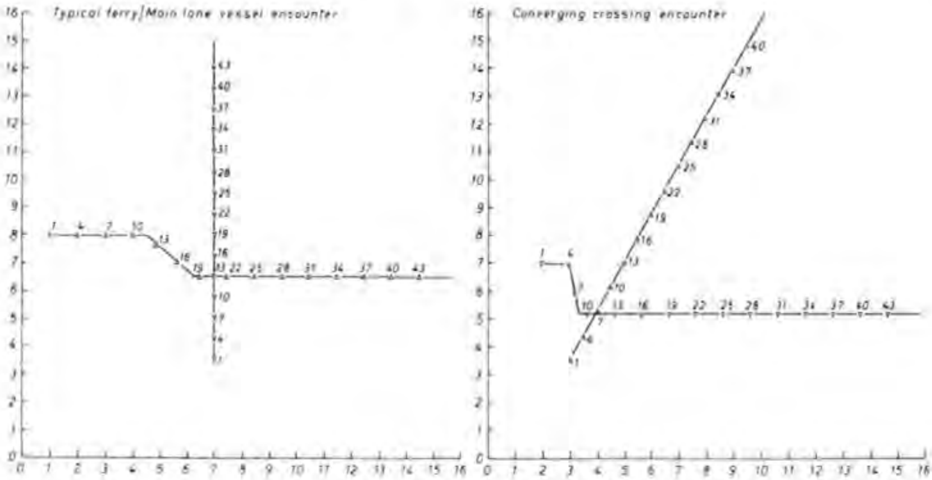
Figs 6 and 7

Head-on encounter (Fig. 7). This shows a head-on encounter between two vessels, both of 20 kt. Only one vessel has altered course in this example, although in a green-to-green head-on encounter both vessels would alter course. Two important points arise here; the first is that the model will not allow both vessels to cancel out each other's manoeuvre (one manoeuvre to starboard, the other to port) and the second is that a manoeuvre to port is executed if the encounter has a large negative contribution.

Typical ferry/main lane vessel encounter (Fig. 8). This encounter, with the faster give-way vessel (20 kt) is typical of a ferry bound for England meeting a main south-westbound lane vessel (15 kt).

Converging crossing encounter (Fig. 9). In this converging crossing situation, the 20 kt give-way ship makes a substantial alteration of course to starboard to pass clear astern of the stand-on vessel also steaming at 20 kt.

Overtaking encounters (Figs 10 and 11). A parallel overtaking manoeuvre is shown in Fig. 10. The overtaking vessel steaming at 20 kt alters to starboard to pass a 15 kt ship. Fig. 11 demonstrates how the RDRR model simulates a converging overtaking encounter, in which a 15 kt vessel was passing a slower 10 kt ship. On this occasion the overtaking vessel altered course to starboard to parallel the stand-on vessel and resumed course when clear ahead. In situations where it is not convenient to parallel and pass ahead, the computer instructs the overtaking vessel to pass astern of the stand-on vessel.



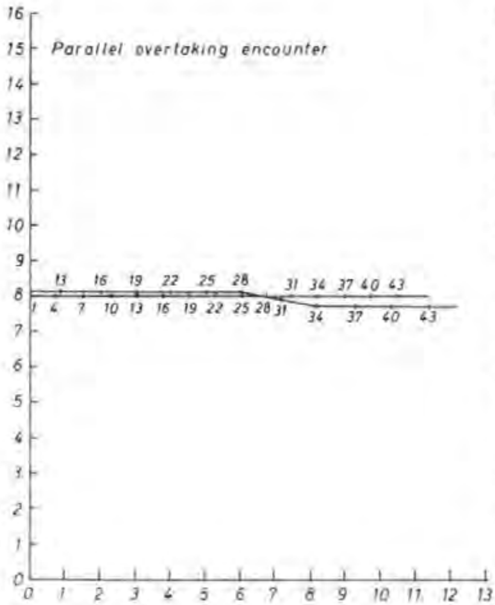
Figs 8 and 9

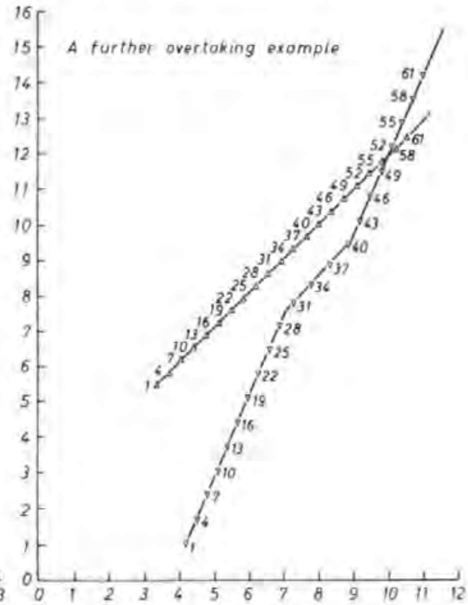
Multi-ship encounter (Fig. 12). Encounters of this complexity rarely occur at sea, but this example demonstrates how the model has the capability of resolving an encounter consisting of more than two vessels on converging courses.

Comparison with ship tracks in the Dover Strait (Fig. 13). Our final form of model assessment is to make a comparison between the 24 h continuous ship traffic simulated by the RDRR model with ship tracks recorded at the Cap Gris Nez radar over a 24-h period. It can be seen that a similar high density of concentrated traffic passes to the north of the Varne light-vessel and a lesser volume passes south both in our simulation and on the French recorded ship tracks. Similarly the angle of the broad fan of ferries destined for and leaving Dover is comparable, showing a tendency for concentrations at the two extreme angles and at an intermediate angle.

7. CONCLUSIONS. We have demonstrated the way in which ships' manoeuvres may be simulated realistically with a computer by the use of a mathematical model employing the concept of circular domains and the RDRR criterion. A selection of two ship encounters have been demonstrated along with examples of the way in which the method can cope with the less frequent three- and multi-ship encounters.

The RDRR/domain manoeuvring model has been used as the basic building block of a computer simulation of a 13 n.m.-long section of the main south-





Figs 10 and 11

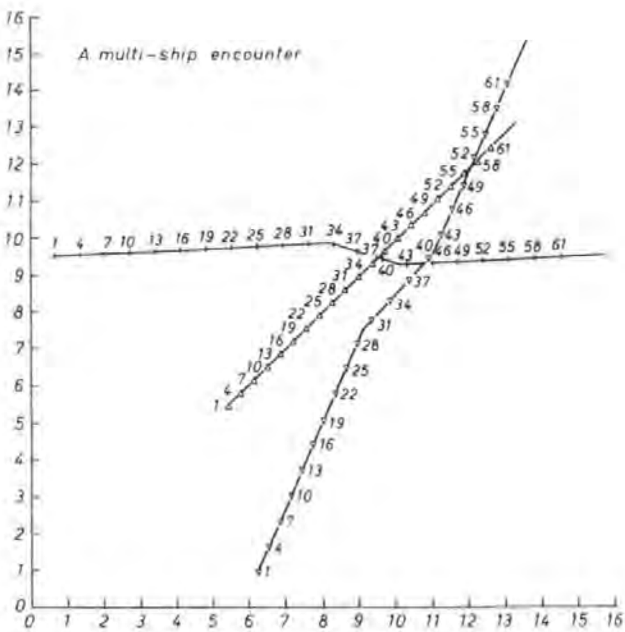


Fig. 12

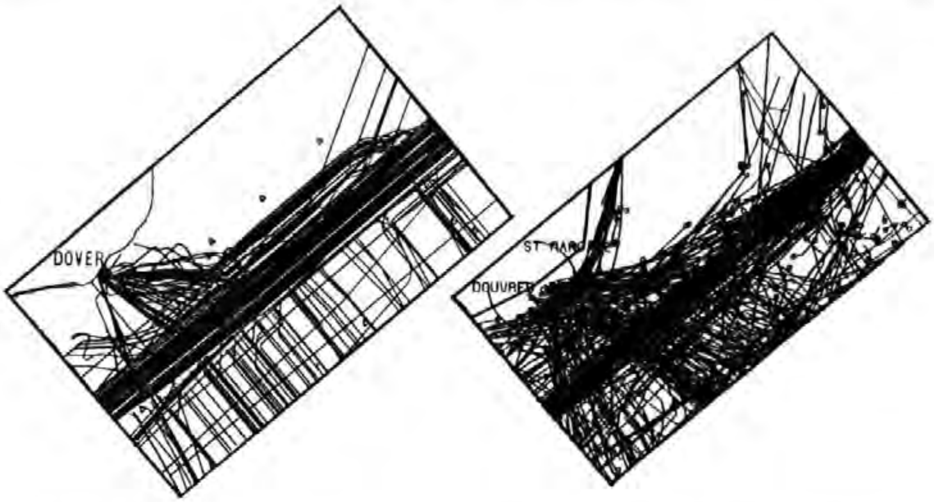


Fig. 13 (left) Traffic generated by computer simulation; (right) traffic observed in Dover Strait

westbound traffic lane in the Dover Strait. Crossing traffic and the adjacent inshore traffic zone were included. Buoys are implemented as stationary targets and depth contours as sets of stationary targets with a higher danger rating than buoys.

The simulation represents a significant advance on previous research work which did not have the facility for ships to manoeuvre out of collision situations; the ships continued on preset tracks. The area simulation described in this paper allows ships to make collision avoidance manoeuvres. It then enables the effect on the traffic flow pattern of these manoeuvres to be studied.

From a theoretical point of view the model aids understanding of the way mariners plan and carry out collision avoidance manoeuvres. It gives a measure of the range at which the manoeuvre is initiated by calculating the RDRR. Also the area around the vessel that the mariner wants to keep clear has been refined to give better and more accurate understanding of the threat domain.

8. FUTURE DEVELOPMENTS AND APPLICATIONS. The practical applications of the research work derive mainly from the area simulation capability. The method provides a useful management tool to evaluate, in advance, the effect on the traffic flow of constraints upon the system such as modifications to the traffic separation scheme. Similarly in an emergency the effect of a constraint, such as the wreckage of a sunken ship in the traffic flow, can be assessed to enable immediate traffic management action to be taken to reduce the danger to other vessels in the area. Additionally, the likely consequences of modifying one of the rules for preventing collision at sea could be investigated by programming the model to manoeuvre in accordance with the proposed rule.

Similarly an untried collision avoidance system (CAS) could be tested by allowing a proportion of the vessels in the simulation to use the logic proposed to govern the CAS whilst the remainder would retain the normal manoeuvring characteristics of mariners. Another application could be in the logic of a collision avoidance system itself. The RDRR model could be used to give a warning to a mariner at some preset time before he would be expected to take collision avoidance action.

Finally, as a training aid, targets in training simulators currently do not usually carry out collision avoidance manoeuvres. The reality would be increased if the ships were manoeuvred by the model so that they look like realistic targets on the student's radar screen.

As the RDRR model becomes more widely used and as mariners become safer in their collision avoidance manoeuvres, so there will be a continual need to maintain the RDRR model and update its parameters and logic as the mariners' manoeuvres it simulates change and improve.

9. ACKNOWLEDGMENT. The authors are grateful to the former Department of Industry, National Maritime Institute for providing copies of radar films, HM Coastguard on whose radar the films were made, and to Dr Degré of the Institut de Recherche des Transport in Paris for making available a track plot of 24 h of continuous traffic flow.

REFERENCES

[1] Barratt, M. J. (1973). Encounter rates in a marine traffic separation scheme. This *Journal*, **26**, 458.

[2] Degré, T. and Lefèvre, X. (1978). A simulation model of marine traffic in the Dover Strait. Marine Traffic Symposium, Liverpool, pp. 117–30.

[3] Curtis, R. G. (1978). Determination of mariner's reaction times. This *Journal*, **31**, 408.

[4] Goodwin, E. M. (1975). A statistical study of ship domains. This *Journal*, **28**, 328.

[5] Curtis, R. G. (1977). An analysis of the dangers of ships overtaking. *Proceedings of the Conference on Mathematical Aspects of Marine Traffic*, Academic Press (1979) for the Institute of Mathematics and its Applications.

[6] Curtis, R. G. (1980). The probability of close overtaking in fog. This *Journal*, **33**, 329.

[7] Davis, P. V., Dove, M. J. and Stockel, C. T. (1982). A computer simulation of marine traffic with domains and arenas. This *Journal*, **33**, 215.

[8] Colley, B. A., Curtis, R. G. and Stockel, C. T. (1983). Manoeuvring times, domains and arenas. This *Journal*, **36**, 324.

[9] Davis, P. V., Dove, M. J. and Stockel, C. T. (1982). A computer simulation of multi-ship encounters. This *Journal*, **35**, 347.

[10] Hollingdale, S. H. (1977). Can mathematics help the mariner? *Proceedings of the Conference on Mathematical Aspects of Marine Traffic*, Academic Press (1979) for the Institute of Mathematics and its Applications.

DISCUSSION

Dr P. DAVIS (Plessey Marine): The method of inputting the desired course of the vessels on a grid is novel, but is it robust enough to prevent vessels ending up going to the wrong port? The main reason for smoothing the domains in my work was to prevent discontinuities at the boundary of stand-on/give-way-type situations. How does the use of varying size domains cope with this problem, particularly as a manoeuvre for one vessel may alter the situation for another? What has priority within your model – running aground or avoiding collision?

Mr COLLEY: It would not be possible for a ship to be misrouted as the destination of a ship is held as one of the identifying parameters in the model. All ships bound for a particular destination use the same course grid. Thus if a ship moves off its course due to collision avoidance, it will follow a new track to its destination. The philosophy behind the model is that the navigator on a ship has a clear idea of the type of encounter and hence there is no confusion as to choice of domain, and it does not change its size during a collision avoidance manoeuvre. Preference in the model is given to avoidance of land rather than collision with a ship if a choice has to be made. However, if the choice is between manoeuvring for a buoy or a ship, avoidance of collision with the ship takes priority.

Captain A. R. H. ROGERS (MOD): Does the model assess the effect of reducing speed?

Mr COLLEY: At the moment alteration of course is the manoeuvre implemented in the model. This was chosen as an easier manoeuvre to identify from radar films, but the capability to allow for reduction in speed might make the model more realistic.

Dr CURTIS: It has been seen in films of the Dover Strait that commercial ships have a marked preference for altering course rather than slowing down.

Dr G. LEWISON (Department of Trade and Industry): I agree that speed reductions are not generally used as collision avoidance manoeuvres, but ferries sometimes make a round turn in order to lose ground. Has the model shown such manoeuvres? Also has the model been run with through rogues or crossing rogues which might be expected to generate a disproportionate number of encounters? I presume that the model would be used to analyse the effects of such traffic: can the authors say how much they have run the model, and have they looked at the variation in the volume of ferry traffic which in the peak month of August is almost equal to that in the main lanes?

Dr CURTIS: The simulation model sometimes produces the manoeuvre by ferries or other vessels of taking a round turn. We have not as yet input any through rougues or crossing rogues as our philosophy so far has been to model the average mariner who behaves in accordance with the terms of collision avoidance regulations, etc.

Captain FOXHUNTLEY (FMS Co.): Large tankers tend to maintain courses and speeds under all circumstances with the pretext of having restricted manoeuvring room due to deep draught. This has been observed to be true even in deep water. Whereas commercial shipping in general tends not to reduce speed, ferries on the other hand have no reluctance to reduce their speed if necessary. Returning to the first point about different domain size for different manoeuvres, the problem is that an alteration of course to avoid a close quarters situation can involve a ship in far more complicated manoeuvres.

Mr COLLEY: We have certainly observed from the traffic films the tendency for ferries to slow down and to look for gaps in the shipping passing down the main lane.

Dr STOCKEL: We have not found it necessary to have different domain sizes once a manoeuvre has begun because of our assumption that the ship will be under control of a navigator who will correctly assess each situation in adequate time.

Mr J. PARKER: I am interested in the possible uses of the simulation model to test collision avoidance systems such as the Calvert manoeuvring system or the present system of crossing traffic routes at right angles.

Dr CURTIS: The model in the future could certainly make a contribution to discussion on collision avoidance systems. It could be used to evaluate the effect of a ship equipped with a system encountering a mariner-controlled vessel. The model could even form the logic of a collision avoidance system to warn the mariner just before he should manoeuvre. The model could evaluate the effect of different crossing angles. Changes could be made to have ships crossing at different angles instead of the present mandatory right angles and the effects analysed.

Captain ROGERS: Has any measure of the tidal stream been incorporated?

Mr COLLEY: At present it has not been incorporated, but this would be a future development with allowance made for the effects produced, e.g. in contour domains.

Captain HUGHES (Southampton College of Nautical Studies): Has the question of operating under nocturnal conditions or restricted visibility been looked into?

Dr CURTIS: The simulation has been planned as a daylight clear-visibility situation. To take into account nocturnal conditions or restricted visibility it would be necessary to reconfigure the simulation with parameters changed where necessary.

Dr E. M. GOODWIN (Polytechnic of North London): Supporting Captain Foxhuntley's point on the behaviour of large tankers, it was certainly found in my research on ship domains that dimensions of the domain increased generally with increase in ship size, but for large tankers there was a sharp drop in domain dimensions, suggesting that all other ships should manoeuvre clear of the very large one. Having seen the behaviour of the ships in the simulation with respect to land, it would be interesting to know the dimensions of the domain for land and buoys used in the model.

Mr COLLEY: The domain dimensions for both buoys and land were arbitrarily taken as circles of radius 0·5 nautical miles.

Mr J. P. O'SULLIVAN (Sperry Electronic Systems): It would be interesting to know how this model compared to the model developed by Degré in terms of the density of traffic used. Since the simulation is all in good visibility presumably the clear weather collision regulations are used. It was interesting to hear of the difficulty experienced in detecting speed changes from the traffic film; this is a general problem in radar data processing.

Mr COLLEY: The same volume of traffic along the main routes was assumed as in the Dover Strait film so the work is comparable to that of Degré. The important difference is that Dr Degré did not use collision regulations. His ships did not manoeuvre; they moved on preset courses. We use the clear-visibility Collision Regulations to simulate the effect of collision avoidance manoeuvres.

Captain W. S. JAEGER (President, Mercantile Marine Service Association): In answer to a previous speaker VLCCs can be as manoeuvrable as other ships. For instance 90% of all VLCC types have bridge control and are able to alter course or speed as a means of avoiding situations. When transitting the Straits of Dover any master would have his engines on manual standby or, in the case of bridge control, all systems prepared for immediate use.

Dr GOODWIN: Having heard some suggestions for potential use for the model from the floor it would be interesting to hear the comments of the speakers on the practical uses for the model.

Dr CURTIS: The major uses may be seen in two categories. Firstly as a means of helping understand how a mariner behaves and handles the vessel. Secondly, the simulation can be used to evaluate any changes in the Collision Regulations or in routing schemes or to predict the problems if say part of the main shipping lane was blocked.

Dr LEWISON: How much does the model cost to run a 24-hour simulation? If the costs are not too high then it could be used to investigate the effects of perturbations in the flow, such as the introduction of a cable-laying ship, a drilling rig or a bridge in order to provide guidance on the appropriate traffic management measures.

Dr STOCKEL: The cost would be very roughly around £100.

Dr GOODWIN: Is it likely that the model could be made readily available on a microcomputer?

Dr STOCKEL: The model is too large for the present generation of micros but in the future this might well be possible.

Captain FOXHUNTLEY: The quality of the personnel on some vessels leaves much to be desired, and I would have thought the size of program required to handle the randomness of their actions would be such that no computer could handle it!